A RECONNAISSANCE OF SULFUR RESOURCES IN WYOMING, COLORADO, UTAH, NEW MEXICO, AND ARIZONA

BY F. L. WIDEMAN

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F. L. Wideman[1/]

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SUMMARY

This paper lists resources of sulfur in Wyoming, Colorado, Utah, New Mexico, and Arizona, an area comprising approximately 522,600 square miles. Sources of sulfur occuring within the region are sulfur ore, pyrite and pyritic ores, and natural gases and petroleum. Data concerning these sources are presented on a statewide basis.

Some of the known deposits of sulfur ore are surficial and of fumerole origin; other deposits have resulted from oxidation of pyrite or sulfide ores of copper, lead, and zinc. The deposits are small and the sulfur is distributed erratically in them. There is a small production from some of the deposits, and the material produced is used as soil conditioner.

Sulfur and sulfuric acid, produced as byproducts of the mining and the oil and gas industries, are the principal contribution of the area to the domestic sulfur industry. The reserves of metallic and gaseous sulfides in the area are an important sulfur resource.

Wyoming

Deposits of sulfur ore in Wyoming have been exploited intermittently in the past as sources of sulfur. Currently, the sulfur-bearing rock, produced in small tonnages, is used as soil conditioner. There has been little, if any, production of pyritic or sulfide ores in Wyoming for several years. There are no known significant reserves of pyrite and sulfide ores in Wyoming. Byproduct sulfur is extracted from sour gas near Worland and Powell, towns in the northwestern part of the State. The reserves of oil and gas in subsurface reservoirs underlying parts of the State contain a large reserve of hydrogen sulfide, much of which could be recovered.

Colorado

Deposits of native sulfur occur in the western part of Colorado. They are small in size and of two types: (1) Fumerole deposits and (2) deposits resulting from the oxidation of metallic sulfides. The occurrence of pyrite and pyritic ores of base and precious metals is widespread in the mountainous part of Colorado. The ore deposits of Leadville, Climax, Kokomo, Red Cliff, and Rico contain substantial reserves of sulfur in the form of pyrite and other sulfide minerals. The tailings ponds in two of these districts and mines and mine dumps elsewhere in the State contain additional reserves of pyrite. The liquid fuels produced from known reservoirs in eastern and northwestern Colorado do not contain enough sulfur gases to be considered a source of sulfur.

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Utah

The Cove Creek sulfur beds are the largest and best known of the surficial sulfur deposits in Utah. These, and other smaller deposits in various parts of the State, are of fumerole origin. Sulfuric acid is produced as a byproduct of the smelting industry at Garfield, Utah. Concentrates from the copper concentrators at Magna and Arthur are the principal source of the sulfur gases used in the process. Deposits of sulfide ores, principally those of the Bingham district, and pyrite impounded in tailings ponds, contain the largest known reserve of sulfur in the State. The salt domes in southeastern Utah and southwestern Colorado do not contain deposits of sulfur, insofar as is known. The liquid fuels currently produced in Utah are not a source of sulfur.

New Mexico

There are fumerole deposits of native sulfur in two localities in New Mexico. They are small, and the sulfur is distributed erratically in the enclosing rocks. The ore deposits of New Mexico contain a reserve of sulfur combined with base metals. Most of this reserve is near Silver City, the county seat of Grant County, in the southwestern part of the State. The oil and gas fields of southeastern and northwestern New Mexico contain a large reserve of hydrogen sulfide. Two plants extract sulfur from natural gas produced in the southeastern part of the State, and another plant extracts sulfur from gas produced in the northwest part.

Arizona

There are no known deposits of native sulfur ore of any significance in Arizona. Sulfide ores of copper, lead, and zinc, with the pyrite associated with the ores, constitute a large reserve of sulfur in Arizona. The deposit of pyritic material that encloses the United Verde ore body at Jerome is of considerable size and contains a large reserve of sulfur. Mill tailings ponds at several copper concentrators contain reserves of pyrite-bearing material. Sulfuric acid is produced at Benson and Inspiration from sulfur obtained from commercial sources. Sulfuric acid has been produced in the past from smelter gases, but currently no acid is produced in the State from such sources.

INTRODUCTION

This paper is one of a series on the mineral resources of the Nation. It describes deposits of sulfur ores and other sources of the element in Wyoming, Colorado, Utah, New Mexico, and Arizona. This group of States has reserves of sulfur ore, pyrite, and other sulfide ores, and natural gas and petroleum containing hydrogen sulfide.

Published reports and records have been used as sources of information, and credit is given in the present report. However, most of the data have been obtained from owners and operators through field contacts or written requests for information.

Field work was begun in August 1953, and the report was completed in July 1956. An attempt has been made to present data concerning the known deposits and sources in the States mentioned. Data concerning some occurrences or sources may have been omitted because of the limited time and the large area covered by the work.

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ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance given him by members of the staff of the Bureau of Mines, who supplied information concerning deposits of sulfur ores and reservoirs of natural gas and petroleum. Other staff members aided by preparing, reviewing and editing the report. The deposits that were inspected and the industrial plants that were visited are numerous. It is impractical to record the names of all the men and companies supplying data for this publication, but the author wishes to thank them for their kind cooperation and courtesies.

WYOMING

Occurrences of sulfur and the presence of hydrogen sulfide associated with other gases in Wyoming have been known for many years. Hydrogen sulfide is emitted from springs near Cody, Thermopolis, and other localities. A sulfur occurrence in the southwestern part of the State was mentioned in literature as early as 1882.2/

Production of sulfur in Wyoming began in 1906, during which year sulfur-bearing rock was mined and treated by steam near Cody, Park County. Production from these deposits stopped in 1907 and was started from deposits near Thermopolis, Hot Springs County, in 1908.3/ Since the latter date, small, intermittent production has been recorded from both localities. Interest has also been shown from time to time in deposits in Sunlight Basin and along the Shoshone River in Park County, and in a warm-springs deposit near Auburn, Lincoln County. Production of sulfur became of economic consequence in 1950, with construction of a plant to extract sulfur from natural gases in the Big Horn Basin. Since then, two more sulfur-extraction plants have been built in Wyoming.

All known deposits of native sulfur ore in Wyoming are surficial fumerole deposits. They are small, and erratic distribution of the sulfur makes it difficult to reliably estimate the grade and tonnage they contain. The location of the native sulfur deposits and the plants that extract sulfur from natural gas are shown on figure 1.

Sulfur Deposits Near Cody, Park County

Small, irregular-shaped deposits of native sulfur occur in an area 3 to 5 miles west and southwest of Cody. The area is approximately 2-1/2 miles in length and 1/2 to 3/4 mile in width, and extends from the Shoshone River on the north to Sulfur Creek on the south and southwest (fig. 2). The deposits lie on bench lands near the eastern flank of Cedar Mountain at altitudes of approximately 5,200 feet. The bench lands slope gently to the east and are scored by shallow gulleys near the deposits. The slopes become steeper to the west near Cedar Mountain. To the south, tilted sedimentary formations form hogbacks; to the west the folded sedimentary formations form Cedar Mountain, which rises above the surrounding terrain.

Cody, the principal town in the western part of the Big Horn Basin, has a population of 3,800 persons. A branch line of the Chicago, Burlington & Quincy Railroad connects Cody with the Billings-Denver branch of the same railroad near Frannie, Wyo., 50 miles northeast of Cody. Hard-surfaced highways connect Cody with other towns of the basin and State. Two of the highways traverse the area near the sulfur deposits.

2/ Day, David T., Geol. Survey, Mineral Resources of the United States, 1882 and 1884.

3/ Geol. Survey, Mineral Resources of the United States, 1906, 1907, and 1908.

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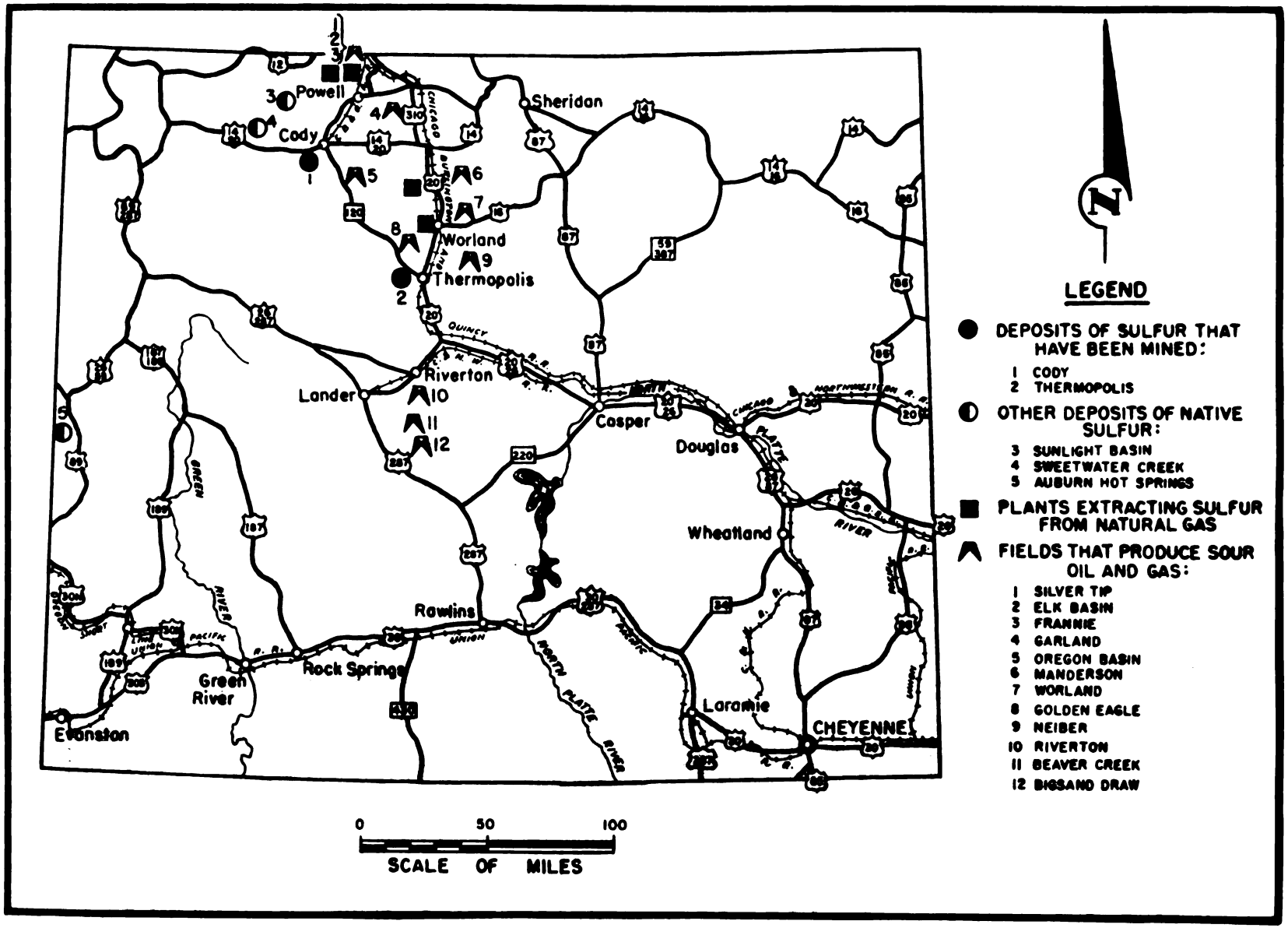

Figure 1. - Location of sulfur deposits, sulfur-extraction plants, and sour gas and oil fields of Wyoming.

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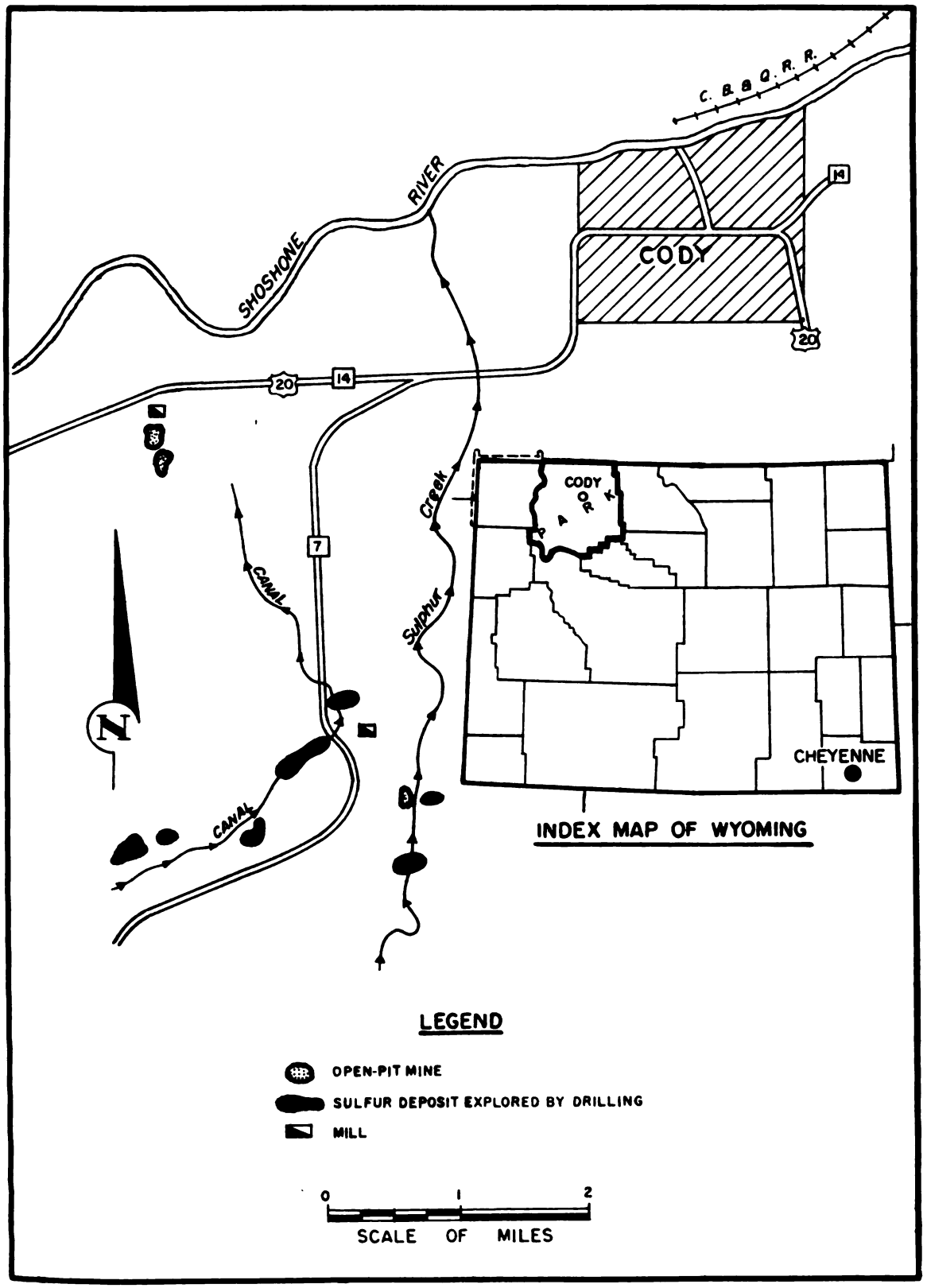

Figure 2. - Location map, Cody sulfur deposits, Park County, Wyo.

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The climate in the vicinity of Cody is semiarid; the annual precipitation averaged 9.11 inches over a 29-year period. More than one-half the precipitation falls in 4 months, April through July. The precipitation is sufficient to sustain a growth of grass and weeds and occasional sage and other desert bushes. The daily and seasonal variations in temperature are large, the average minimum being below 10° F. in January and February and the average maximum above 80° F. during July and August.

Production of sulfur near Cody was begun in 1906 and ceased in 1907.[4/] Mining was resumed in 1916, when economic conditions caused by World War I gave impetus to the sulfur industry. Two companies mined the deposits in 1916, and a third company began operations in 1917.[5/] It is reported that ore assaying 35 percent sulfur was mined by open-pit methods. The sulfur was extracted by placing perforated cars loaded with hand-sorted ore in a retort and subjecting the ore to steam under pressure. The melted sulfur was collected in vats. The operation was inefficient and of short duration. The southern part of the area was explored by core drilling in 1951. A beneficiating plant designed to recover sulfur by flotation, with purification by melting, was completed during December 1951 and operated intermittently until June 1952. No production has been recorded from the deposits since the latter date.

The rocks in the area of the deposits range in age from Permian to Recent. Sulfur occurs in veins in travertine overlying the Cody and Powell terraces (Pleistocene?), which are composed of gravels, sands, and silts. Most of the production has come from irregular-shaped deposits in the Phosphoria formation (Permian), which consists of a series of limestones, sandstones, and shales with chert and a phosphatic member near the base. There is evidence of faulting, especially along the southern edge of the mineralized area.

It is reported that sulfur ore over 20 feet thick was found in several of the holes drilled during 1951. One hole drilled to a depth of 63 feet is reported to have bottomed in rock containing 25 percent sulfur.

Elemental sulfur occurs as small crystals and in earthy masses in a gangue of gypsum, travertine, limestone, and sandstone. Samples of high-grade ore contain as much as 50 percent free sulfur, and samples of rock taken a short distance away are essentially barren. A sample from the coarse-ore bin of the mill of the Wyoming-Gulf Sulphur Corp., and analyzed by a Bureau of Mines laboratory, contained 29.8 percent elemental sulfur and less than 0.002 percent selenium.

Sulfur Deposits of Sunlight Basin, Park County

The sulfur deposits in Sunlight Basin are approximately 60 miles by road northwest of Cody, Park County. Two groups of deposits that are similar in all characteristics occur in the basin. The main group is near Sunlight, Gas, and Yellowstone Creeks toward the southern part of Sunlight Basin (fig. 3). The other deposits are on Little Sunlight Creek about 3 miles north of the main group. All deposits are within the boundaries of the Shoshone National Forest.

The deposits may be reached from either Cody, Wyo., or Red Lodge, Mont. From Cody the route is northwesterly along the Clark Fork secondary highway for 16-1/2 miles, thence westerly 23 miles to Sunlight Basin via an unimproved road that is

4/ Work cited in footnote 3.
5/ Geological Survey, Mineral Resources, 1916 and 1917.

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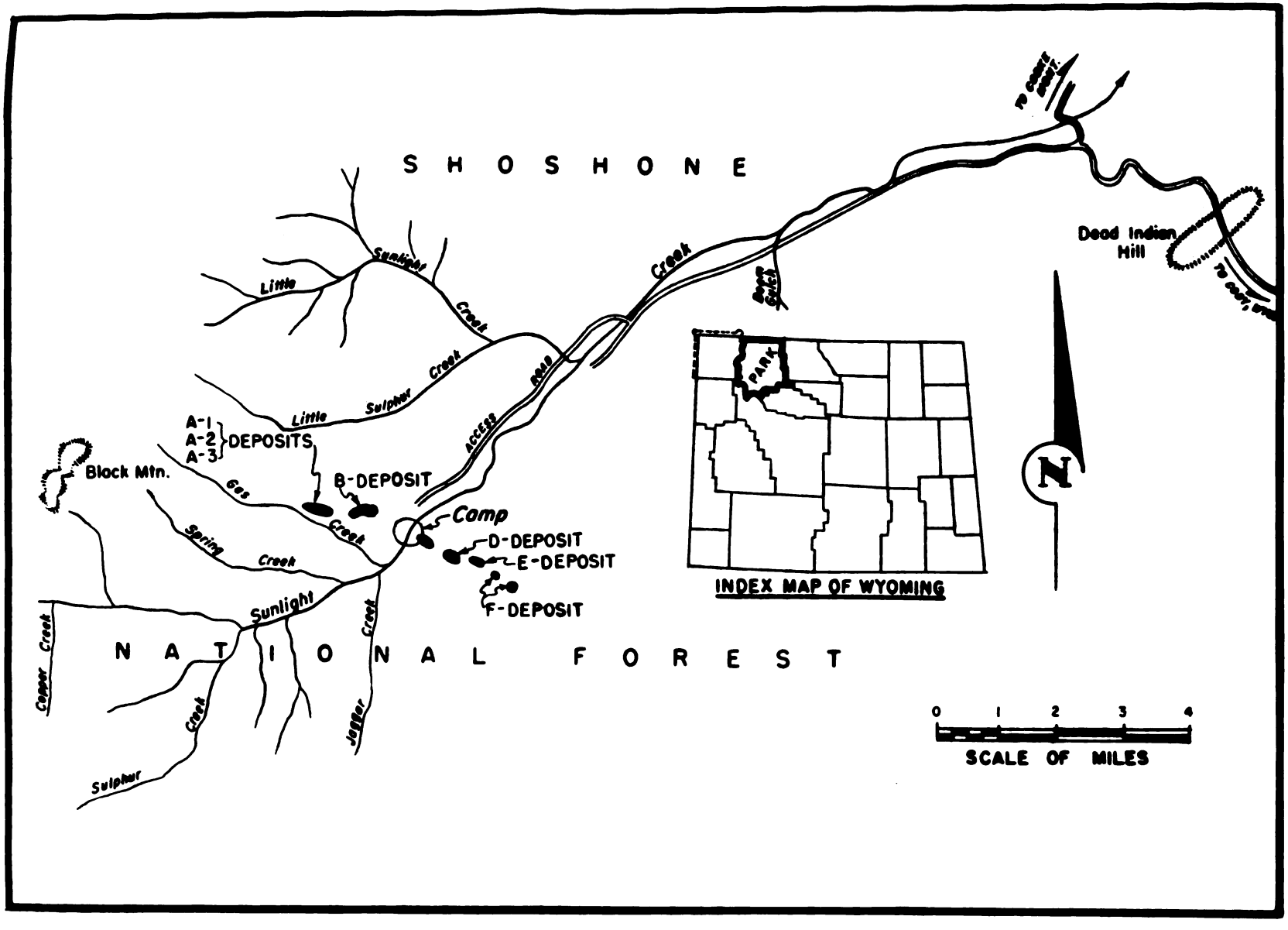

Figure 3. - Location map, Continental Sulfur & Phosphate Corp., Sunlight Basin, Park County, Wyo.

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tortuous and has steep grades, especially on Dead Indian Hill. The deposits are 21 miles southerly by graded road from a point where the road enters Sunlight Basin.

The better access to the area is via U. S. Highway 12 westerly from Red Lodge, Mont., for about 52 miles, and thence southerly along the Clark Fork River by graded road about 30 miles to a point where the road from Cody enters Sunlight Basin. The latter route has fewer sharp curves, and its grades are less steep than those on the road from Cody, Wyo.

There are a few cattle ranches in the basin, and crops of alfalfa and grain are raised with irrigation water from creeks that originate in the perennial snowfields of Sunlight and other peaks. Summers are mild and pleasant, but winters are cold, and snowfall is often sufficient to hamper traffic to and from the basin.

The deposits are in a region of bold relief at altitudes 7,100 to 7,700 feet above sea level, and the mountain peaks to the south rise to altitudes exceeding 12,000 feet. The deposits lie along ridges, spurs, and steep slopes. Some deposits are relatively remote from streams; others are near creeks that flow northeasterly to Clark Fork of the Yellowstone River. Most slopes are covered by a growth of coniferous trees, except in the immediate vicinity of the deposits, where sulfur gases issue from vents and prevent growth of any vegetation.

The sulfur deposits occur near fumeroles in Tertiary volcanic rocks of andesitic to basaltic composition. Small inliers of limestone, dolomite, and shale (Devonian?) are associated with sulfur deposition near one of the westernmost deposits. The volcanic rocks adjacent to the deposits have been bleached and are white or light gray. The volcanic rocks that have not been bleached are dark gray.

Trenching and drilling indicate that most of the sulfur occurs near the surface as a coating of minute crystals on rock fragments. Some sulfur occurs in veinlets, as drusy fillings in fissures, and as linings or fillings in occasional solution cavities in limestone. The deposits in the southern part of the basin lie in such a position as to indicate they occupy a fracture zone.

During the summer of 1951, four of the largest deposits were explored by auger drilling and bulldozer trenching. A limited amount of core drilling was accomplished on two other deposits earlier the same summer. The drilling indicated that most of the sulfur lies within 6 feet of the surface, except in 1 deposit, where it is associated with sedimentary rocks.

There has been no production, except for a few carloads of ore that was mined during 1952 and 1953 for metallurgical testing.

The deposits along Little Sunlight Creek have not been explored to date. They are similar in character and type and appear to be smaller than those near the southern part of the basin.

Sweetwater Creek Deposits, Park County

A group of small sulfur deposits occurs near the Wapiti Forest Ranger Station, about 32 miles west of Cody and 20 miles south of the sulfur deposits in Sunlight Basin, from which they are separated by high mountains. The deposits lie on Sweetwater Creek, about 2 miles north of its confluence with the North Fork of the Shoshone River. The area may be reached by traveling westerly from Cody via U. S. Highway 14 to a point 1/2 mile west of the Wapiti Forest Ranger Station. Here a dirt road that leaves the highway to the north gives access to the deposits.

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The deposits occur on a narrow strip of land, approximately 1/4 mile long, that lies east of the river. The area in which sulfur has been found does not exceed 20 acres. The sulfur mineralization cements fragments of dark, igneous rock that have been deposited in shallow fans at the mouth of dry washes.

There has been no production from the deposits and they do not appear to contain any appreciable quantity of sulfur.

Sulfur Deposits Near Thermopolis, Hot Springs County

Sulfur occurs along both flanks of an eroded anticline 3 to 4 miles northwest of Thermopolis. The known deposits are situated in an area about 1 mile square. Sulfur is associated with travertine and alluvium that lies unconformably upon tilted older rocks. It is also found in altered limestone and shale. The deposits have been worked intermittently since 1908. Ore mined from 1945 to 1947 was used, without beneficiation, as soil conditioner.

Thermopolis is in the southern part of the Big Horn Basin and has a population of 2,900 persons. The Denver-Billings branch line of the Chicago, Burlington & Quincy Railroad passes through Thermopolis, the shipping point for a large area. Hard-surfaced highways - U. S. 20 and Wyoming State Highway 120 - connect Thermopolis with other towns of north-central Wyoming. The sulfur deposits are reached by traveling about 3-1/2 miles northwest from Thermopolis on Highway 120, thence by dirt roads to the north and northwest. The open pits on the southwest flank are visible from the highway (fig. 4).

The sulfur occurs on the flanks of a limestone ridge that extends northwestward from Thermopolis. Altitudes vary from 4,600 feet in Owl Creek Valley to more than 5,100 feet along the crest of the ridge. Owl Creek, a small, perennial stream, flows along the northeast flank of the ridge and empties into the Big Horn River north of Thermopolis. A plain, deeply dissected by gulleys, slopes gently upward in a southerly direction from the base of the ridge to the Owl Creek Mountains, 20 miles distant. The northeastern flank of the ridge merges into Owl Creek Valley to the northeast.

The climate in the vicinity of Thermopolis is arid, the annual rainfall varying from 3 to 10 inches. The summers are hot, with showers of short duration. Winters are severe, with considerable wind. The vegetation consists of a sparse growth of grasses, weeds, and sagebrush, except along streams, where there is enough water for irrigation.

Production of sulfur was begun in 1908, during which year a plant was built to treat ores from pits along the northeast flank of the anticline.[6] Sulfur was extracted by a thermal process similar to that used near Cody. The recovery of sulfur was poor, as indicated by the sulfur content of the refuse piles that remain near the plant site. No data are available concerning the total production, but the size of the pits and refuse piles indicates that production was small. A plant using a similar process was built on the opposite flank of the ridge in 1922 or 1923.[7] This venture was also of short duration.

6/ Work cited in footnote 3.
7/ Geol. Survey, Mineral Resources of the United States, 1923.

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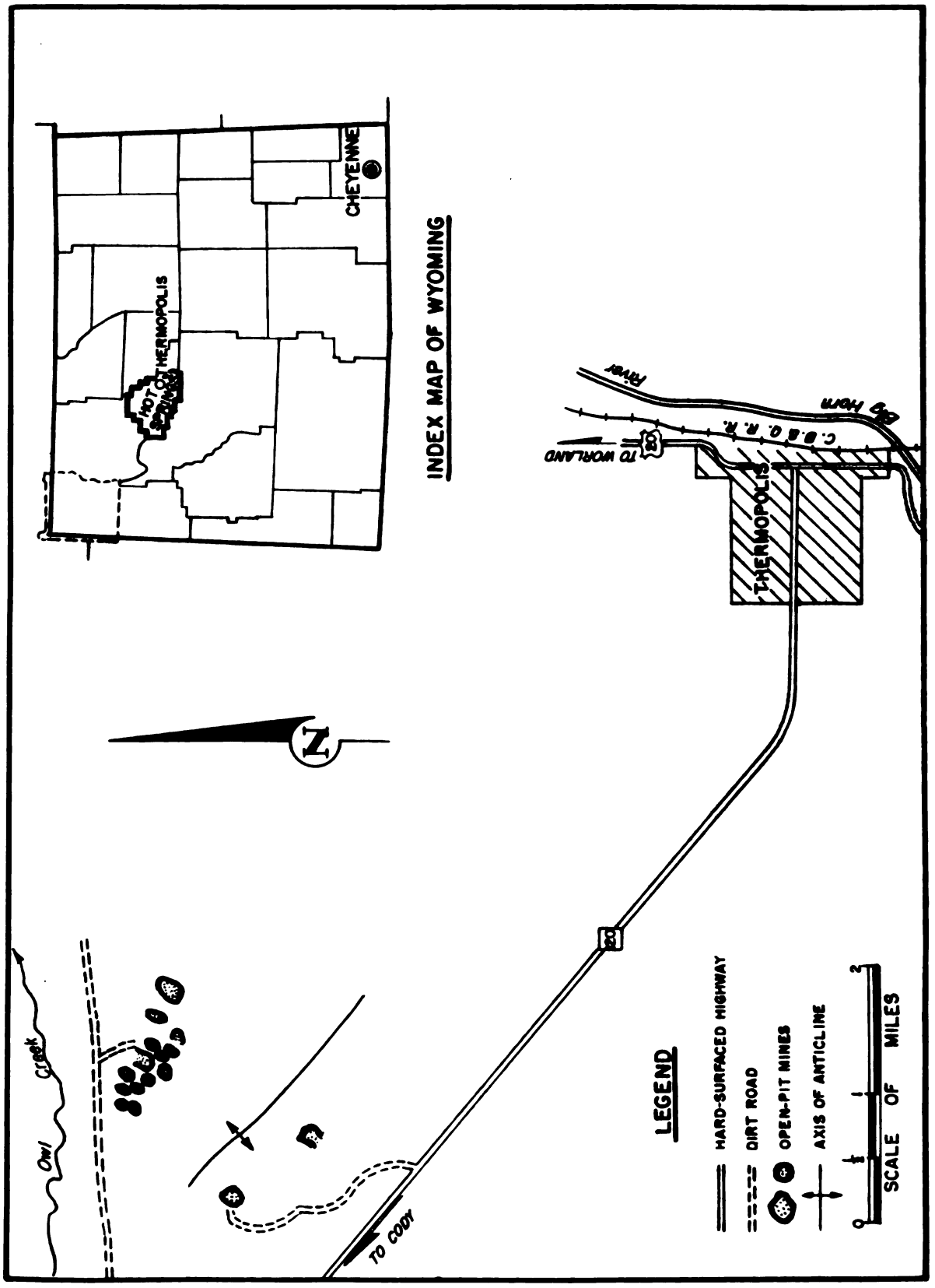

Figure 4. - Location map, sulfur deposits near Thermopolis, Hot Springs County, Wyo.

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The Bureau of Mines conducted an exploratory project on the deposits on the southwestern flank of the anticline during 1944. The work consisted of rehabilitating old workings, sinking test pits, and trenching. The project work and results are described in Bureau of Mines Report of Investigations 3964, Exploration of the Brutch Sulfur Deposits, Hot Springs County, Wyo., by Forest H. Majors.

It is reported that approximately 15,000 tons of ores was shipped for use as soil conditioner during 1945 and 1947.

Deposits on the southwest flank of the anticline were drilled during 1951. Sixteen holes were completed in an area that is approximately 750 feet long and averages 200 feet in width. Bulldozer trenching was also a part of the exploratory work.

The sulfur deposits are associated with travertine, alluvium, and the Embar formation. The Embar formation is divided into two formations, the Phosphoria (Permian) and the Dinwoody (Triassic). The Phosphoria formation is composed of carbonaceous, phosphatic shales, mudstones, and impure limestones, and the Dinwoody is composed of fine-grained, dolomitic mudstone and shale.

Two forms of free sulfur are found in the deposits - the yellow, crystalline variety and a massive variety that is brown to black. The first-mentioned variety is found in cavities and crevices, and the latter seems to be a replacement of limestone or associated with the tarry oil residue in the Phosphoria formation. Soluble salts of sodium, calcium, magnesium, and aluminum are associated with the sulfur. Gypsum is commonly associated with the travertine that, with limestone and shale, is a host rock for the sulfur.

Sulfur has been mined from deposits on both limbs of the anticline in numerous pits, opencuts, shafts, and room-and-pillar stopes. It is reported that some workings exposed sulfur to a depth of slightly more than 100 feet. The open pits are accessible for examination, but many of the small pits, shafts, and stopes have caved. The noxious gases, hydrogen sulfide and sulfur dioxide, issue from caved workings.

Auburn Hot Springs, Lincoln County

The Auburn Hot Springs are about 2-1/2 miles north of Auburn in the extreme west-central part of Wyoming. Auburn is a village of about 300 population, along the western side of Star Valley near the foothills of the Caribou Mountains. A gravel road traverses the western part of the Star Valley and passes near the deposits. Afton, Wyo., (population 1,200), is the largest town in the vicinity and is about 15 miles from the deposits. Cokeville, Wyo., is the nearest shipping point and is 55 miles distant, on the Union Pacific Railroad system. Dairying and ranching are the principal industries in Star Valley. Summers are mild and pleasant, but winters are severe, with subzero temperatures, and during some winters the snowfalls are heavy.

Springs feed 3 pools, 2 of which are roughly rectangular and the third roughly circular. The rectangular pools are approximately 80 and 135 feet in width by 150 feet in length, and the circular pool is approximately 75 feet in diameter. The pools are surrounded by travertine, which contains some sulfur, lining cavities and crevices. The bottoms of the pools are covered with sludge that is reported to be as much as 100 feet deep in one of the pools. Samples taken from the edges of the pools are reported to have contained as much as 90 percent sulfur. Samples

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taken by Bureau of Mines engineers during 1951 of the sludge and from small stockpiles contained 3 to 40 percent free sulfur and less than 0.01 percent selenium.

Two unsuccessful attempts have been made to utilize the sludge from the pools. During the winter of 1948-49, sludge was excavated from one of the pools by a dragline and dried in a rotary kiln. A small tonnage of the material was sold as soil conditioner. Difficulties were experienced because the sludge ignited in the kiln, and production stopped. A few tons of sludge was pumped into shallow drying ponds in 1952 and dried by solar evaporation. The life of the operation was short, and there is no record of any sulfur sales.

Other Sulfur Deposits in Wyoming

The only available information concerning other deposits in Wyoming are references to a deposit in the southwestern part of the State.[8/] It is reported to be in the Uinta Mountains, about 30 miles from Evanston, Uinta County. Little interest was shown in this deposit after 1888.

The area was not visited during the period of field work on which this report is based.

Reserves of Sulfur Ores in Wyoming

The known reserves of native sulfur ores in Wyoming are small compared with the reserves of the United States. Because the deposits are surficial, selective mining by open-pit methods would be the most suitable method of exploitation. The percentage of extraction of the ore should be high, as relatively small quantities of ore would be lost in mining.

Sulfur and Hydrogen Sulfide From Petroleum and Natural Gas Produced in Wyoming

Most of the elemental sulfur produced in the States included in this report is recovered from the sour natural gases of Wyoming. Hydrogen sulfide is produced also in refining crude oils from certain Wyoming fields (fig. 1). There is a large reserve of hydrogen sulfide in the subsurface reservoirs of hydrocarbons in the central and north-central parts of the State. The reserve of hydrogen sulfide is estimated to exceed 6,100,000 long tons, from which over 5 million tons of sulfur could be produced.[9/]

Most of the data concerning the production and reserves of sulfur presented in this section of the report were supplied by the late Ralph H. Espach, Chief, Petroleum and Natural-gas Branch, Region IV, Bureau of Mines Laraine, Wyo., Petroleum and Oil-Shale Experiment Station. Additional data were supplied by officials of the many natural-gas-and petroleum-producing companies.

The oil and gas fields are in the Big Horn and Wind River Basins, which are separated geographically by the Owl Creek Mountains. The Big Horn Basin extends from near the Montana border southward to the mountains. It is bounded on the east by the Big Horn Mountains and on the west by the Absaroka and other ranges. The Wind River Basin extends from the Owl Creek Mountains southward for about 50 miles to the Antelope Hills and the Green Mountains. It is bounded on the west

8/ Work cited in footnote 2.

9/ Espach, Ralph H., Sources of Hydrogen Sulfide in Wyoming: Ind. Eng. Chem., vol. 42, Nov. 1950, pp. 2235-2238.

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by the Wind River Range and on the east by ranges of hills. The maximum east-west extent of the basins is about 90 miles. The basins are broad valleys bordered on all sides by mountains and hills. The basins are drained by the north-flowing Big Horn River and its major tributaries, the Shoshone, Greybull, and Wind Rivers. Altitudes vary from approximately 3,600 feet where the Big Horn River enters Montana to over 13,000 feet attained by some peaks in the surrounding mountains. The average altitude in the interior of the basins is about 5,000 feet.

The major towns in the Big Horn Basin are Cody (population 3,800), Powell (population 3,800), Lovell (population 2,500), Greybull (population 2,300), Worland (population 4,200), and Thermopolis (population 2,900). Branch lines of the Chicago, Burlington & Quincy Railroad traverse the Big Horn Basin. Riverton (population 4,100) and Lander (population 3,400) are the largest towns in the Wind River Basin. A branch line of the Chicago & Northwestern Railroad passes through Riverton and ends at Lander. A hard-surfaced highway system connects the major towns in both basins, and improved roads lead to the oil and gas fields.

The climate is semiarid. Summers are hot and dry, with considerable wind. Winters are frequently severe, with subzero temperatures and ground blizzards. The hills of the basin sustain a growth of grasses, weeds, and low brush. The plains are cultivated near the larger streams where water is available for irrigation.

Production of gas in the Baxter Basin in the southwestern part of the State during 1922 resulted in discovery of hydrogen sulfide. The production of gas in the Garland field in 1927 and petroleum in the Oregon Basin and the Frannie field in 1927 and 1928, respectively, also resulted in finding hydrogen sulfide gas. Large volumes of hydrogen sulfide were discovered when oil was found in the Tensleep sandstone underlying Elk Basin. Subsequently, other oil and gas fields yielding hydrogen sulfide were developed as follows: Worland and Big Sand Draw in 1946, Neiber Dome in 1947, Silver Tip in 1948, Beaver Creek and Riverton in 1949, Slick Creek in 1950, and Manderson in 1951.

A plant to extract sulfur from natural gas was erected in Elk Basin, near Powell, during 1949. A large sulfur-extraction plant was erected near Worland in 1950, and a third plant began operating in Elk Basin in 1953 (fig. 1). These plants extract the sulfur by modified Claus processes, using bauxite as a catalyst. The plants were designed for a total daily production of approximately 500 tons of sulfur.

A sulfur-extraction plant near Manderson began production in 1955. Manderson is a small town 20 miles north of Worland, via U. S. Highway 20.

By January 1, 1952, approximately 147,300,000,000 cubic feet of hydrogen sulfide had been estimated to exist in association with free gas and solution gas. Table 1 summarizes information concerning the more important sources of hydrogen sulfide in Wyoming. In preparing the estimates contained in the table, fairly accurate data were available for some reservoirs, but others had not been developed completely. If future developments should extend the size of the reservoirs, the presence of larger volumes of hydrogen sulfide would be indicated. Several other oil and gas fields in the State produce gas containing hydrogen sulfide, but either the amounts are small or the fields have not been developed enough to permit reliable estimates of the hydrogen sulfide.10/

10/ Work cited in footnote 9.

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TABLE 1. - Reserves of hydrogen sulfide and sulfur available in oil and gas fields in Wyoming as of January 1, 1952[1/]

Name of field	County	Formations containing hydrogen sulfide	Type of associated gas	Approximate hydrogen sulfide content of gas by volume, percent	Volume of hydrogen sulfide, million cubic feet	Amount of hydrogen sulfide, 1,000 long tons	Available sulfur, 1,000 long tons[2/]
Elk Basin	Park	Tensleep	Solution gas[3/]	13.0	18,473	766.1	640.9
		Madison	do.	6.0	2,250	93.3	78.1
Silver Tip	Park	Phosphoria	do.	31.0	16,725	693.6	580.3
		Tensleep	do.				
Garland	Big Horn	Embar	Free gas[4/]	2.0	200	8.3	6.9
		Tensleep	Free and solution gas	1.5	750	31.1	26.0
		Madison	Free gas	.5	100	4.1	3.5
Manderson	do.	Phosphoria	Solution gas	23.0	4,600	190.8	159.6
Worland	Washakie	do.	do.	30.0	79,500	3,297.1	2,758.3
Slick Creek	do.	do.	do.	19.8	10,791	447.9	374.4
Neiber Dome	do.	do.	do.	37.2	2,535	105.1	88.0
Golden Eagle	Hot Springs	do.	do.	9.0	322	13.4	11.2
		Tensleep	do.	40.0	746	30.9	25.9
Big Sand Draw	Fremont	Embar	Free gas	2.0	1,700	70.5	59.0
Beaver Creek	do.	Tensleep	Solution gas	4.4	1,513	62.7	52.5
Riverton	do.	Phosphoria	Free gas	1.0	371	15.4	12.9
		Tensleep	Solution gas	18.0	6,682	277.1	231.8
Long Creek	do.	Phosphoria	Free gas	1.0	32	1.3	1.1
Totals					147,290	6,108.3	5,110.4

1/ Work cited in footnote 9.
2/ Based on sulfur equaling 94 percent of hydrogen sulfide and 89 percent plant conversion.
3/ Gas in solution in petroleum in subsurface reservoirs.
4/ Gas existing as dry gas in subsurface gas reservoirs.

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Another source of hydrogen sulfide is the refining of crude oils produced from the fields listed in table 1 and the relatively high-sulfur-content crude oils from other fields in Wyoming. This source has not been included in table 1. Approximately 30 tons of hydrogen sulfide is produced daily by a refinery that processes 20,000 barrels of crude oil a day. There are three refineries in the Billings, Mont., area that process crude oil produced in Wyoming and in so doing, produce about 50 tons of hydrogen sulfide daily.11/

Table 2 presents information concerning several oil refineries that process crude oil from the Big Horn Basin. The information was supplied by the companies mentioned in the tables.

Uses of Sulfur Produced in Wyoming

Most of the sulfur produced in Wyoming by sulfur extraction from natural gas is used by the paper-pulp industry, and the petroleum refineries and chemical companies use most of the sulfur that is not so consumed. The hydrogen sulfide recovered in refining crude oil enters the fuel lines of the refineries and is burned under the boilers. All sulfur ore produced during recent years has been used as a soil conditioner.

TABLE 2. - Oil refineries processing crude oil from the Big Horn Basin

Company	Location of refinery	Source of oil	Barrels per day	H_2S, percent
Carter Oil Co.	Billings, Mont.	Elk Basin, Wyo.	22,000 to 25,000	0.1 by volume.
Continental Oil Co.	do.	Frannie Elk Basin	8,500	2.2 by weight.
Farmers Union Central Exchange	Laurel, Mont.	Byron Garland	12,000	0.0075 by weight.1/
The Texas Co.	Casper, Wyo.	Various fields in Big Horn Basin	15,000	0.0039-0.0079 by weight.
Sacony Vacuum Oil Co.	do.	Big Horn Basin	7,300	0.14 by weight.
Standard Oil Co. of Indiana	do.	Wind River and Big Horn Basins	11,000	0.02 by volume.2/
Husky Oil Co.	Cody, Wyo.	Oregon Basin	5,000	3/

1/ Desulfurization plant in planning stage. Yield estimated at 10 tons of sulfur a day.
2/ No facilities to remove hydrogen sulfide.
3/ All hydrogen sulfide absorbed with caustic soda or flared with fixed gases.

11/ Work cited in footnote 9.

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COLORADO

The development of deposits of elemental sulfur in Colorado began about the beginning of the present century, although their existence was previously known. It is reported that sulfur was produced from Gunnison County before 1906 and that the development of deposits in Mineral County began in 1905. Since these early years there has been intermittent production of small tonnages of sulfur, principally during emergencies. Currently, the only production is a minor tonnage of sulfur-bearing sandstone that is ground and mixed with other materials and sold as a soil conditioner.

Deposits of native sulfur of limited size have been reported in six counties: Delta, Dolores, Gunnison, Mesa, Mineral, and Montezuma. All deposits lie west of the Continental Divide, except for the deposits in Mineral County, which lie on both sides of the divide. The deposits are small in size and surficial in type, and the sulfur is erratically distributed in the host rocks. The locations of the deposits are shown on figure 5.

Sulfur Deposits in Delta County

Fumarole deposits of native sulfur occur in Delta County in sandstone, impure limestone, and shale. One deposit that has been mined is reached by traveling 14 miles east of the town of Delta via State Highway 92, and thence southerly by dirt road for about 1/2 mile. A second deposit being mined on a small scale is about 2 miles south of the small town of Lazear (fig. 6). It is reported that other deposits along the Gunnison River are known, but no information is available concerning the size or grade of sulfur.

The Delta County deposits are found in bluffs along the Gunnison River. In the vicinity of the deposits the river is confined to a narrow valley, from the edges of which bluffs rise as high as 50 feet above the valley floor. Beyond the bluffs, bench lands slope upward toward mesas. The altitude at the deposits is about 5,000 feet.

Delta, the principal town in the vicinity, has a population of 3,700 persons. It is situated on a branch line of the Denver & Rio Grande Western Railroad and on U. S. Highway 50. The sulfur deposits are reached by traveling along a hard-surfaced highway (Colorado 92) easterly from Delta and thence by dirt roads in a southerly direction.

The climate is semiarid, but much of the land in the valley is cultivated and irrigated with water from the Gunnison River and its tributaries.

The deposits occur in sandstone, impure limestone, and shale of the Mancos formation (Cretaceous). The sedimentary beds dip gently northwestward. Cold-water springs in the vicinity of the deposits have deposited small travertine terraces. Sulfur gases are emitted from the springs and from vents in the rocks. The western deposit has been formed along an arroyo north of the river, and sulfur-bearing rocks are exposed for a length of approximately 300 yards along each side of the arroyo. The maximum exposed thickness of the mineralized sandstone, shale, and limestone is about 8 feet. The eastern deposit occurs in the sandstone bluffs along the river. Here the mineralized rock is exposed for about 100 feet in length and 18 feet in thickness.

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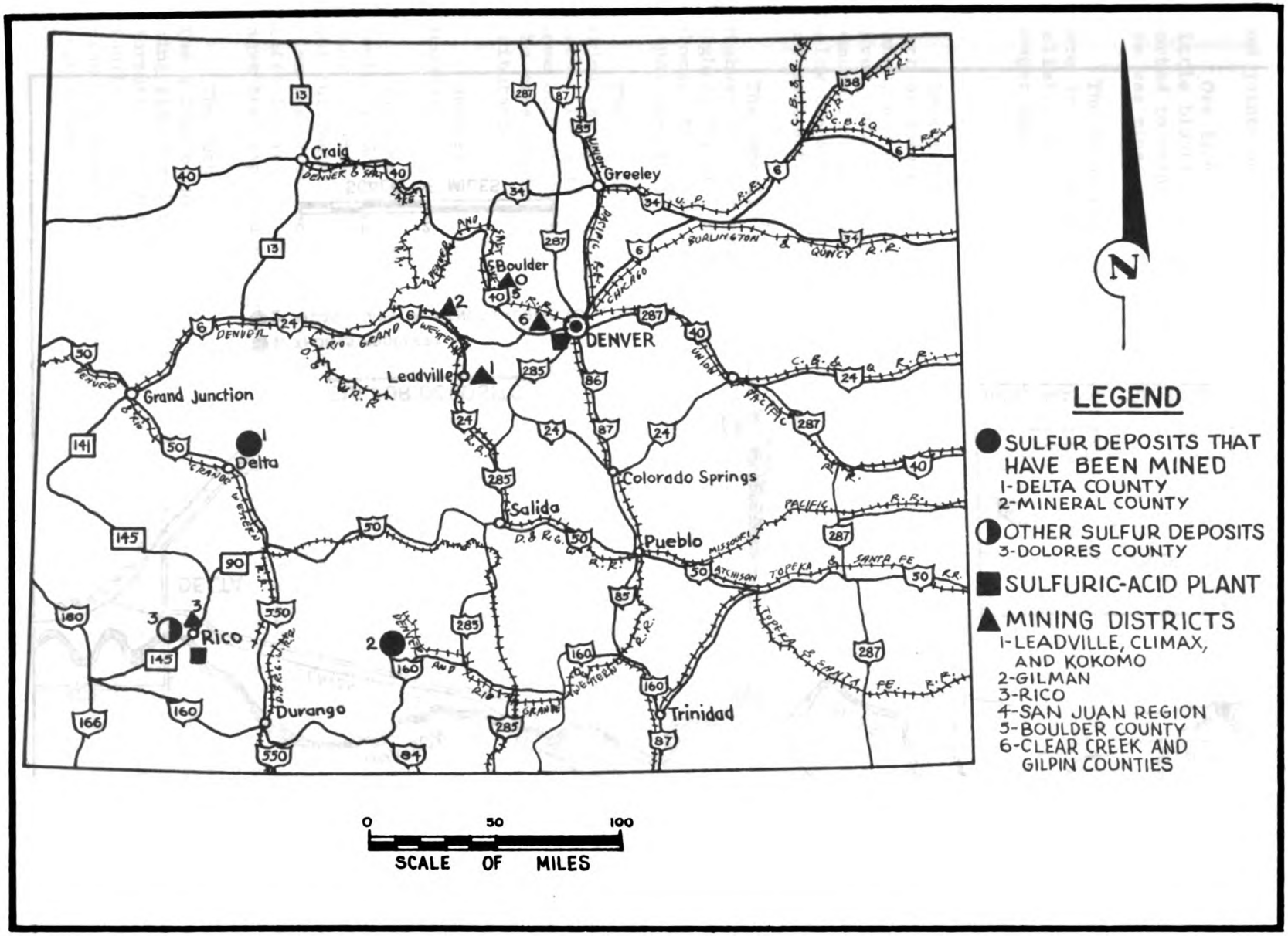

Figure 5. - Location of sulfur deposits, sulfuric-acid plants, and mining districts of Colorado.

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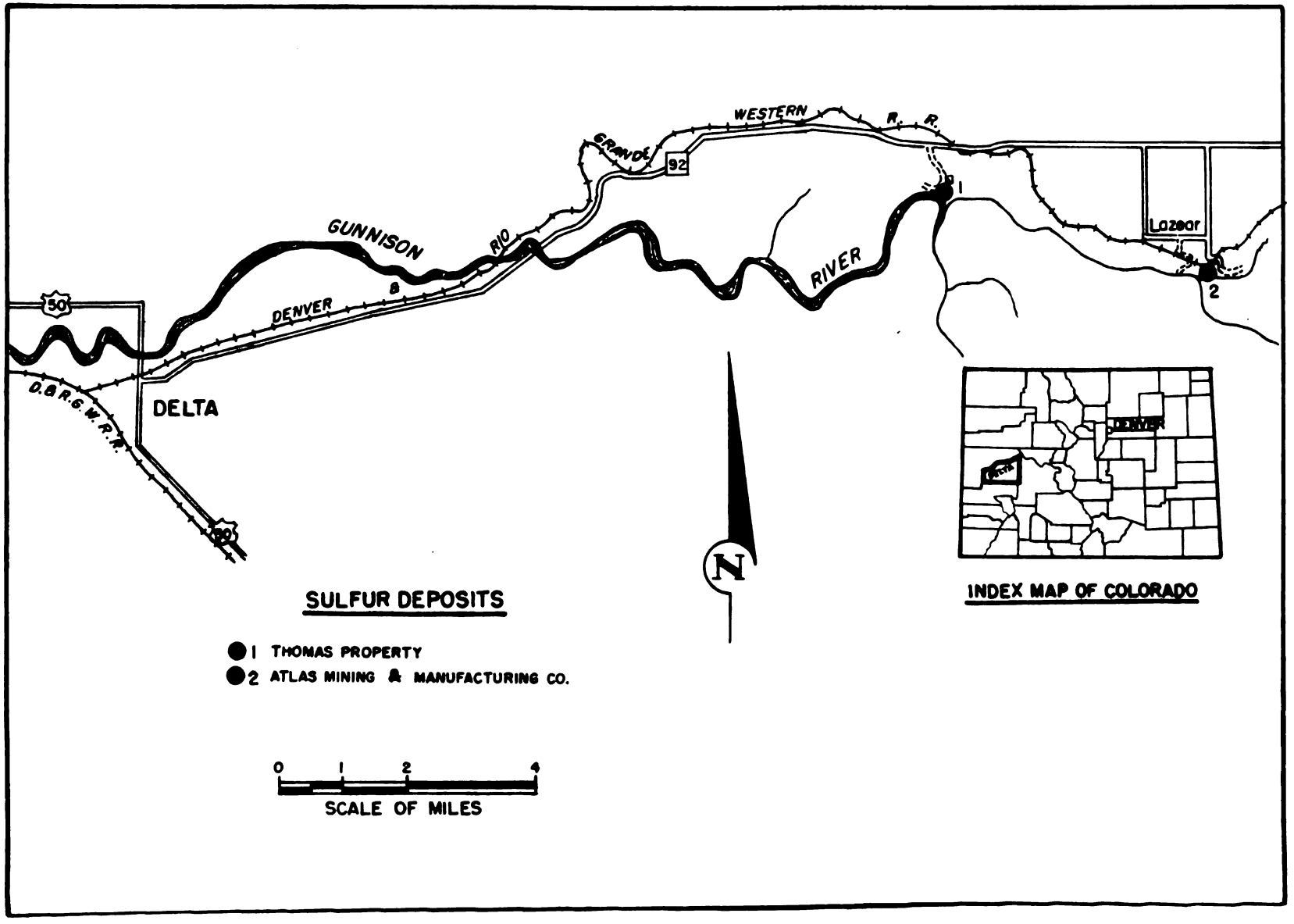

Figure 6. - Location map, sulfur deposits near Delta, Delta County, Colo.

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The sulfur occurs as small, yellow crystals and botryoids along bedding planes and joints and in vugs in the host rocks.

Ore from the eastern deposit is pick-mined from the base of a sandstone bluff. Little blasting has been necessary to date. The ore is loaded by hand and roughly sorted to maintain a grade of approximately 40 percent sulfur. It is reported that ore was mined and loaded mechanically from the western deposit.

The deposits have not been extensively explored, although six core-drill holes were drilled on the western deposit about 1950. It is not possible to estimate reliably the grade and tonnage of sulfur-bearing sandstone in the deposits from the meager amount of work completed to date.

Sulfur Deposits in Dolores County

Several small, surficial deposits of sulfur have been found in the eastern part of Dolores County (fig. 7). They occur near Dunton, a post office and guest ranch, and are found in a belt that extends from a point near the West Dolores River, southerly approximately 5 miles to Stoner Creek. The deposits are of fumarole origin, and the best grade of sulfur does not extend more than a few feet below the surface. The prevailing country rocks in the vicinity of the deposits are sediments that have been intruded in places by igneous dikes.

The deposits may be reached by traveling northeasterly from Dolores by State Highway 331 approximately 37 miles, thence by truck trails and horse trails. Highway 331 is a graded, dirt road that is passable most of the time, except when blocked for a few days by heavy snowfalls. Dolores (population 800) is the principal town in the vicinity.

The deposits are in an area of bold relief, characterized by narrow, steep-sided canyons. A dense growth of fir, spruce, and aspen trees covers much of the area. The altitude of most of the deposits is approximately 9,500 feet, although some occur at higher elevations. The altitudes of some peaks immediately east of the area exceed 12,000 feet. The area is drained by the West Dolores River and its tributaries.

Summers are mild and pleasant, but winters are severe, with considerable snowfall.

The area was prospected for precious metals before the beginning of the present century. Some silver, lead, and zinc ores have been produced from the vicinity of Dunton. Underground workings were driven near some of the deposits at this time, but information concerning their extent could not be obtained. No particular attention was given to the sulfur deposits until 1949, when a shortage of sulfur stimulated interest in many possible sources of the element. Several of the deposits have been explored recently by bulldozer trenches and shallow test pits.

The rocks that outcrop in the area are of sedimentary and igneous origin. The sulfur occurs as a cementing material in soil and rock fragments and also bedding planes and in the interstices of red sandstone thought to belong to the Dolores formation of Upper Triassic age. The deposits appear to have been formed near faults, as indicated by the displacement of beds and formation of breccia. Alteration and bleaching of the igneous and sedimentary rocks usually indicate sulfur deposition.

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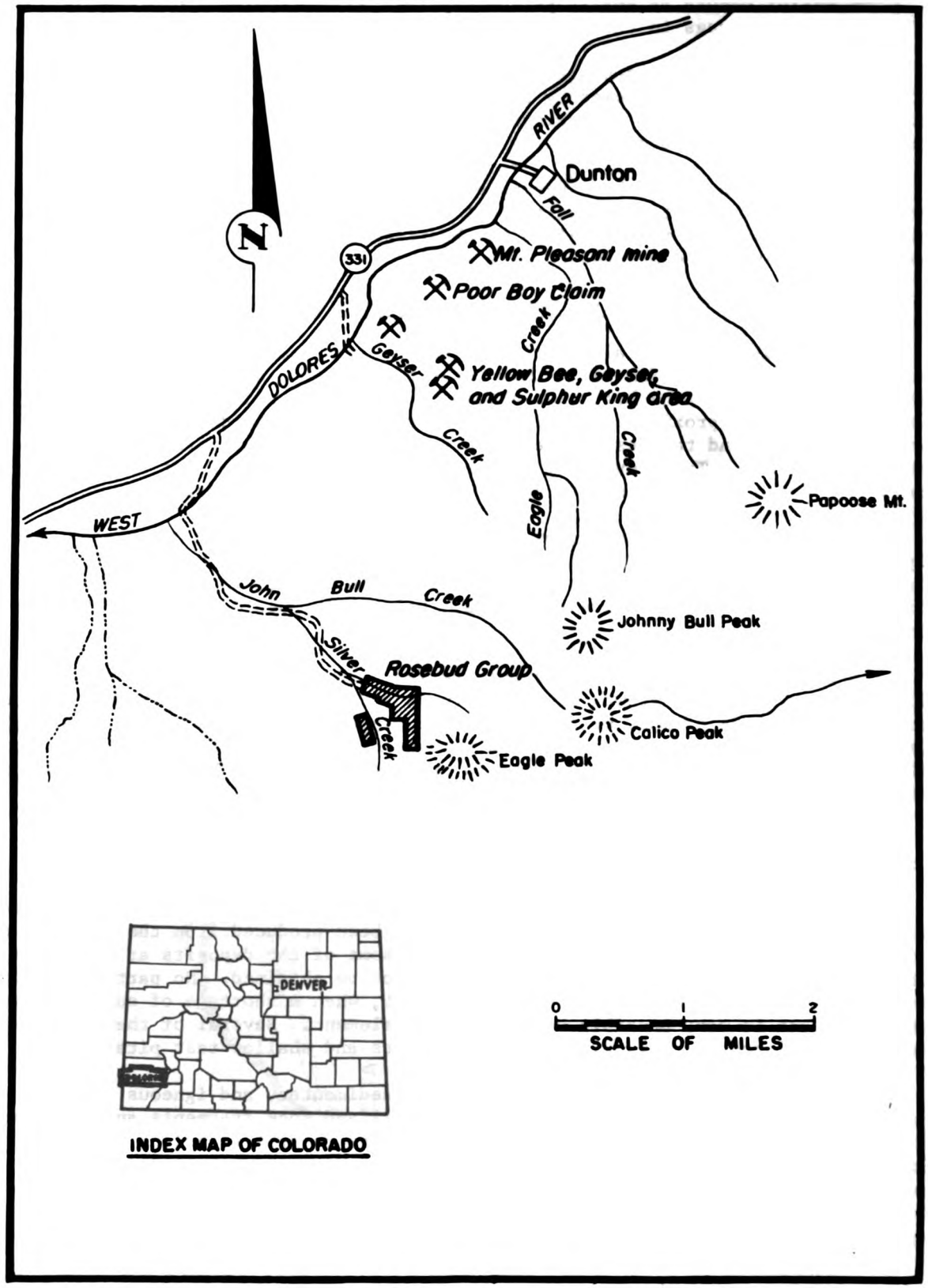

Figure 7. - Location map, sulfur deposits near Dunton, Dolores County, Colo.

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Many of the springs in the area are depositing sulfur at present, although some deposits are near fumaroles that are no longer active. At some of the deposits hydrogen sulfide is emitted with enough velocity to be audible. Wood has been charred and metal corroded at considerable distance from some of the fumeroles. In other instances springs exhibit geyser action with gas bubbling vigorously through the water.

The deposits lie near stream beds or on ridges, but the larger deposits are near the base of slopes where soil and debris have been cemented by sulfur. Trenching on some deposits during recent years has disclosed that the best grade of sulfur ore occurs within 1 to 3 feet of the surface. Below these depths the sulfur content diminishes rapidly, and the mineralization is confined to bedding planes and interstices in the sandstones. The report that some of the old underground workings encountered sulfur ore could not be verified, but no sulfur-bearing rock was observed on any waste dumps.

The sulfur has been deposited as small, yellow crystals and earthy masses. In addition to cementing debris and depositing along bedding planes in sandstone, it forms thick coatings in vents and channels.

The deposits have been explored most extensively by stripping and trenching with a bulldozer. Most of this work was accomplished on the largest deposit, known as the Rosebud, on Silver Creek. A 100- by 300-foot area was stripped and trenched. No work was done on the small, disconnected outcrops of sulfur that occur near the base of a resistant sandstone, exposed along the creek for an additional 500 feet. Six other deposits with smaller outcrops have been partly explored by trenches, pits, and adits.

Sulfur Deposits in Mineral County

Two sulfur deposits, the Trout Creek and Middle Fork, have been found in Mineral County. The 2 are 5 miles apart but are similar in all respects. The deposits occur in altered igneous rocks and appear to have originated from hot springs related to volcanism during the Miocene period. The sulfur ore is of good grade, but the deposits are small in lateral extent. The occurrences are sporadic and do not continue to appreciable depths.

The Trout Creek area is 23 miles southwest of Creede on the eastern slope of the Continental Divide. The Middle Fork deposits are approximately 5 miles southwest of the Trout Creek area on the opposite side of the Continental Divide. The Middle Fork deposits are on the west branch of the Middle Fork of the Piedra River, a tributary of the Colorado River system. The deposits can be reached by horseback from a ranch 17 miles southwest from Creede, but the Middle Fork deposits can be reached more readily from near Pagosa Springs. A wagon road, in disrepair, follows Trout Creek and East Trout Creek to the Trout Creek deposits, and the Middle Fork deposits can be reached from the Trout Creek deposits by horseback. The trip is long and requires at least 3 days.

Creede, the county seat of Mineral County (population about 700), is a mining camp and the terminus of a narrow-gage, branch line of the Denver & Rio Grande Western Railroad system. Pagosa Springs (population 1,700) is in Archuleta County and is situated on another branch line of the Denver & Rio Grande Western Railroad.

Local history indicates that the deposits were first prospected in 1880. Mining began on the Trout Creek deposits about the beginning of the present century;

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but little, if any, sulfur was produced. Operations were resumed in 1917. It was estimated that the deposits then contained 30,000 tons of ore averaging 50 percent sulfur. Evidently operations were unprofitable, except during periods of high sulfur prices, and work ceased in 1921 or 1922. According to reliable local information, the minable reserves were essentially exhausted when operations were terminated. The refining process during all operations was simple and similar to that used at other sulfur properties in the western United States at that time. Ore was loaded into perforated cars, which were delivered into retorts and subjected to steam. Some of the sulfur was melted and passed into molds. The gangue remained in the cars and was trammed to waste dumps. During 1950 and 1951 interest was shown in the deposits, chiefly those on the Middle Fork of the Piedra River.

The deposits occur in a region of considerable relief at elevations between 10,000 and 11,000 feet above sea level. The Trout Creek deposits lie a few hundred feet above the creek bed and just above an alluvial flat formed by a small tributary. About 1-1/2 miles southwesterly a short adit driven into a ridge found some sulfur near the surface. Sulfur is exposed just south of the Middle Fork of the Piedra River. A few hundred yards down the creek are a few short, caved adits that were driven in a white, altered rock that carries a few scattered grains of sulfur.

The slopes are covered with dense growths of coniferous trees; grass and sagebrush grow in the narrow valleys of the streams. Mountain peaks along the Continental Divide attain altitudes in excess of 12,000 feet and are devoid of much vegetation. Summers are mild and pleasant, with occasional thundershowers. Winters are severe, with subzero temperatures and heavy snowfalls.

The deposits are in the andesitic breccia division of the volcanic rocks of the Potosi series. In general, the volcanic rocks are essentially horizontal in the vicinity of the deposits. Apparently the Trout Creek deposits occur near a northwesterly trending fissure. An altered zone along the fault passes through the sulfur deposits and continues at least a half mile southeastward. Small outcrops of bleached rock are prevalent along the zone of alteration, as well as in the zones of alteration farther down Trout Creek. The deposits on the Middle Fork of the Piedra River are also in an altered and bleached zone. About 1 mile northwest is a large area of bleached and decomposed breccia. None of the bleached outcrops in the vicinity of the deposits has been explored, except one previously mentioned about 1-1/2 miles southwesterly from the Trout Creek deposits. The bleached outcrops, where inspected, do not appear to contain sulfur.

The sulfur ore is banded and resembles well-bedded tuff. The bands are less than 1/2 inch wide and yellowish-gray or drab. Yellow sulfur also lines fractures in the ore. The drab bands have conchoidal fracture and vitreous luster and burn readily. The yellowish-gray bands are composed of opal and chalcedony, in which many small crystals of sulfur are embedded. A sample taken from the ore bins in 1911 contained 63.4 percent sulfur and no selenium, arsenic, or tellurium.

The Trout Creek deposits were mined through two adits with interconnecting shafts, sublevels, and stopes that are now inaccessible. Pits that probably yielded some of the production are now partly filled with debris. The short adits on the Middle Fork deposits also are caved. It is difficult, therefore, to estimate the reserves of the deposits; but, like other deposits of similar origin, they probably are not large or persistent to appreciable depth.

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Other Sulfur Deposits in Colorado

The deposits discussed below were not examined during 1953. The information presented was obtained principally from published data.

A small tonnage of sulfur was mined and refined from the oxidized zone of a chimney of gold-bearing pyrite in Gunnison County. The mine is about 12 miles southeast of Iola, a station on a branch line of the Denver & Rio Grande Western Railroad. No data are available concerning the production from the mine or during what period it was operated for sulfur. It is reported that the sulfur graded downward into loose pyrite and then into massive pyrite.[12/]

Sulfur deposits, reported to occur in Mesa and Montezuma Counties, were not investigated, as little local information relative to them is available. The deposits in Mesa County are reported to be near Grand Junction. The deposits in Montezuma County are reported to be about 20 miles east of the town of Dolores. These deposits may be similar to those in Dolores County, as they occur in the same general area.

Pyrite and Sulfide Ores as a Source of Sulfur in Colorado

Deposits of pyrite and sulfide ores in Colorado contain significant reserves of sulfur. The occurrence of these minerals is widespread throughout the mountainous part of the State. They occur in sedimentary, metamorphic, and igneous rocks, but replacement deposits in limestone and one deposit in igneous rocks are the largest and most productive. Pyrite in mine dumps and tailings ponds is another source of sulfur.

Pyrite, produced as a byproduct of milling complex ores, is used to manufacture sulfuric acid at Denver and Rico.

Detailed descriptions of the deposits of pyrite and sulfide ores cannot be given because many of the mines are in disrepair. Therefore, factual data are given concerning the more important districts in which the sulfides occur.

Leadville District, Lake County

A substantial but unmeasured reserve of sulfur is associated with the sulfide ore and pyrite deposits of the Leadville district. Mine dumps and tailings ponds contain an additional reserve of pyrite.

The Leadville mining district is situated in the central part of Colorado. It lies on the western slope of the Mosquito Range, and most mines of the district are at altitudes ranging from 10,000 to 12,000 feet. Some mines in outlying areas are at altitudes of about 13,000 feet.

The town of Leadville (population 4,000) is in the western part of the district. The Denver & Rio Grande Western Railroad passes through the district. Hard-surfaced highways, U. S. Highway 24 and State Highway 91, traverse the area. Improved roads lead to more important mines, and primitive roads to the less productive ones.

12/ Aurand, H. A., Mineral Deposits of the Western Slope: Colorado Geol. Survey Bull. 22, 1920, p. 47.

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The Leadville district is one of the most productive in Colorado and ranks high in the United States in total production. The metals produced from the mines are gold, silver, lead, zinc, and copper. Pyrite has been mined in the district for the manufacture of sulfuric acid. Bismuth, iron ore for flux, and manganese-iron ore also have been produced from the Leadville mines. The Arkansas Valley smelter and several mills in the district, treat the sulfide ores produced here and from other districts in the State.

The primary ore deposits may be classified into three main groups: (1) Silicate-oxide deposits, (2) veins of mixed sulfide, and (3) replacement deposits of mixed sulfides. The latter were formed chiefly in formations, locally called limestones but that have been classified as dolomites. In the western part of the district the large replacement deposits or "blankets" lie along fractures or sheets and beneath impervious formations.

Pyrite is the most abundant sulfide mineral in the western part of the district. It is associated with galena and sphalerite in primary ores and occurs as large masses that contain little gold or silver. Such deposits have been mined for pyrite for the manufacture of sulfuric acid.

Climax, Lake County

Climax is in northeastern Lake County 13 miles north of the Leadville mining district. It is near the Continental Divide at an altitude of 11,300 feet. Nearby mountain peaks attain elevations that exceed 14,000 feet. Snow accumulates to considerable depth in the winter, and the summers are mild.

Freight service is available by a branch line of the Denver & Rio Grande Western Railroad from Leadville. Hard-surfaced State Highway 91 passes through the town.

The ore deposit at Climax is associated with pre-Cambrian granite and schist, intruded by dikes of quartz monzonite porphyry. Mineralization was influenced by a stock of quartz monzonite.

The upper part of the ore body is cone-shaped and enlarged downward. In plan, the ore body is a roughly circular band 300 to 500 feet wide surrounding a core that is not ore. The outside diameter of the ore zone on one level is 2,500 to 3,000 feet, and the diameter of the core on the same level is 1,500 to 1,800 feet.

Molybdenite is the mineral of principal economic value at Climax. The Climax Molybdenum Co. is one of the largest producers of molybdenum in the world. Pyrite, scheelite, and some tin are associated with the molybdenum. Molybdenite is recovered first in the mill circuit; then pyrite is removed from the circuit by flotation; and tungsten and tin are recovered after pyrite is removed. The pyrite concentrate is cleaned and shipped to Denver, where it is used as raw material in the manufacture of sulfuric acid.

Kokomo, Summit County

The Kokomo (Tenmile) mining district is in the southwestern part of Summit County. Kokomo, the main settlement in the district, is about 5 miles northerly from Climax, the nearest railroad shipping point. The district lies near the headwaters of Tenmile Creek at the crest of the Continental Divide. Altitudes at the mines vary from about 10,000 feet to almost 12,000 feet.

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The productive ore deposits of the Kokomo district are of two types, replacement deposits of sulfides in limestone and veins of sulfide minerals in siliceous rock. The first type is of the greatest economic importance. The replacement deposits are irregular in size and shape; their bases are irregular, but their roofs are clearly delineated at the top of the enclosing limestone.

The replacement deposits are composed of sulfides with a small amount of gangue. The sulfide constituents are pyrite, pyrrhotite, marcasite, sphalerite, galena, and chalcopyrite. The amount of each mineral varies widely in the same deposit and in adjacent deposits. The deposits can be classified into three groups: (1) Pyrite deposits, (2) pyrrhotite deposits, and (3) mixed sulfide deposits. The latter-mentioned types have commercial interest at present because of their zinc-lead content.

The deposits of pyrite and pyrrhotite are large and contain a significant but unmeasured reserve of sulfur.

Gilman District, Eagle County

The Gilman (Red Cliff or Battle Mountain) mining district is in southeastern Eagle County about 20 miles northwesterly from Leadville. The district covers the area between the towns of Red Cliff and Gilman. Gilman is situated on the top of steep-walled Eagle Canyon at an altitude of approximately 9,000 feet. The Eagle River and the tracks of the Denver & Rio Grande Western Railroad are in Eagle Canyon almost 600 feet vertically below the town. U. S. Highway 24 passes through the area and joins U. S. Highway 6 a short distance north of Gilman.

The greatest production of the district has come from replacement deposits, or mantos of zinc sulfide in limestone. Other types of deposits are fissure veins of pyritic gold ore and complex sulfide ores in pre-Cambrian rocks, small veins of gold and silver telluride ore in quartzite, replacement deposits of pyritic gold ore along beddings in quartzite, and chimneys of pyritic silver-copper ore in limestone. In places, the mantos contain cores of barren pyrite near their lower ends.

The sulfide ores of the district and the pyrite associated with them contain a reserve of sulfur. Nearby tailings ponds of the New Jersey Zinc Co. impound pyrite and gangue minerals separated from the ore. Some of the pyrite was used formerly as a raw material to manufacture sulfuric acid at Denver. The company estimates that 1,800,000 tons of mill tailings with a sulfur content of 30 to 40 percent remain in the ponds.

Rico Mining District, Dolores County

The Rico (Pioneer) mining district is in the northwestern part of Dolores County, one of the southwestern counties of Colorado. The district lies in a small group of mountains detached from the San Juan Mountains to the east and northeast. The town of Rico (population 400) is in the valley of the Dolores River at an altitude of 8,700 feet.

No railroad shipping facilities are available at Rico. Supplies and products of the mines are transported by trucks via State Highway 145.

Much of the ore from the district has been produced from blanket deposits and large, irregularly shaped ore bodies that have formed where veins intersect beds of limestone, gypsum, or brecciated shale.

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The ore is complex, containing gold, silver, zinc, lead, and copper. Some fissures are productive for as much as 150 feet beneath the blanket deposits, below which they contain quartz and pyrite.

The mines of the Rico district have a reserve of sulfur associated with pyrite and sulfide ores. Pyrite, impounded with other minerals in tailings ponds, contains an additional reserve of sulfur.

The Rico Argentine Mining Co. planned to begin producing sulfuric acid from a plant at Rico in 1955, with a capacity of 200 tons of acid a day. Pyrite in mill tailings will be the first source of raw material used in manufacturing the acid.

Western San Juan Region

The San Juan region covers about 12,000 square miles in southwestern Colorado. The area west of the Continental Divide, in parts of Ouray, San Miguel, and San Juan Counties, is highly mineralized, and the mines, tailings ponds, and mine dumps contain an unmeasured reserve of sulfur associated with sulfide ores and pyrite.

The area is characterized by rugged mountains; altitudes vary from 6,000 feet to more than 14,000. It is drained by the Uncompahgre, San Miguel, and Animas Rivers.

Most of the production has been derived from mines near the towns of Ouray, Telluride, Ophir, Silverton, and Rico; the latter has been previously discussed.

There are no railroads in the area. Branch lines of the Denver & Rio Grande Western Railroad pass through Montrose, about 30 miles northerly of Ouray, and Durango, about 40 miles southerly of Silverton. U. S. Highway 550 and State Highways 62 and 145 serve the area. Vehicles equipped with four-wheel drive are necessary to drive over roads to some of the mines.

Uncompahgre (Ouray) District

The Uncompahgre district covers about 15 square miles in the vicinity of Ouray.

The ore deposits are fissure veins, replacement deposits, or deposits that have characteristics of both types. The mineralization may be divided into four groups: (1) Magnetite-pyrite ores, (2) pyritic ore containing copper and gold, (3) pyritic base-metal ores with gold and silver, and (4) siliceous ores of silver, lead, and zinc.

Telluride and Sneffels Districts

The Telluride and Sneffels districts are in San Miguel and Ouray Counties. They are separated by the divide between the San Miguel and Uncompahgre Rivers. The Camp Bird, Smuggler Union, Black Bear, and Tomboy mines were the most productive in the districts.

Most of the production of the districts has come from veins in the San Juan tuff, the lowest member of the volcanic series that covers much of the San Juan area.

The ores are a mixture of pyrite, sphalerite, galena, and chalcopyrite in a gangue of quartz, calcite, and some rhodonite and rhodochrosite. The gold-bearing quartz of the Camp Bird mine fills fissures occurring alongside of or breaking through more massive sulfide veins.

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The reserve of sulfur in the district is correlated to the reserve of sulfide ores of base metals. Tailings ponds at Telluride and Red Mountain contain some reserves of pyrite.

Other Mining Districts in the Western San Juan Area

Pyrite and sulfide ores occur in unmeasured quantities in the mineral deposits of the Iron Springs (Ophir), Mount Wilson, Red Mountain, Animas, Eureka, Mineral Point, Poughkeepsie, and Upper Uncompahgre mining districts.

Boulder County

The principal reserve of sulfur in Boulder County is associated with pyritic-type gold ore and waste dumps resulting from mining ore of this type. Most of the ore has been produced from the Grand Island, Ward, Gold Hill, and Jamestown mining districts.

Boulder (population 20,000) is the county seat of Boulder County. It is about 30 miles northwest of Denver, via the Denver-Boulder Toll Road, or by Federal and State highways. The mining districts lie to the southwest, west, and northwest within 20 miles of Boulder.

The ores generally occur in narrow veins in pre-Cambrian granites and schists. Pyrite, chalcopyrite and, in places, galena are associated with gold and silver, the metals of primary economic importance.

Clear Creek County

Clear Creek County is in the north-central part of Colorado, east of the Continental Divide. Idaho Springs (population 1,800) is the largest town in the county. It is about 30 miles west of Denver, via U. S. Highways 6 and 40. The principal mining districts are Silver Plume, Georgetown, Empire, Dumont-Lawson, Central City-Idaho Springs, and Alice-Yankee Hill.

Most of the ore produced in the county was pyritic gold and silver-lead-zinc ores. The ore deposits are veins in pre-Cambrian granite and schists that have been intruded in places by porphyries.

Pyrite, produced in the county, has been used in manufacturing sulfuric acid at Denver.

Pyrite in the mines and dumps in the county contains an unmeasured reserve of sulfur.

Gilpin County

Gilpin County lies between Clear Creek and Boulder Counties. Central City (population 400) is the largest town in the county. State Highway 119 traverses the county, but the roads to many of the mines have steep grades.

The ore deposition is similar to that in Clear Creek and Boulder Counties, except at the Evergreen mine, which was worked for copper.

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UTAH

Sulfur mining in Utah began over a century ago, soon after the immigration of the early settlers. The Cove Creek sulfur beds, 180 miles south of Salt Lake City, were discovered about 1854.13/ These deposits have been worked intermittently since discovery and were a source of sulfur for several years just before the beginning of the present century. Other deposits in the State have attracted attention from time to time, but none is of economic importance at present (fig. 8).

The native sulfur deposits have been formed by reduction of gases escaping from fumaroles, and sulfur has been found in the oxide zones of base-metal ore bodies. The salt domes, or similar structures in eastern Utah and western Colorado, do not contain sulfur insofar as is known.

Sulfide ores and pyrite associated with them contain a large reserve of sulfur. Tailings ponds, which impound pyrite rejected in milling the ores, contain an additional reserve of sulfur.

Sulfuric acid is produced at Garfield as a byproduct of smelting copper concentrates and ores.

Cove Creek Sulfur Beds, Beaver and Millard Counties

The Cove Creek sulfur beds occur in Beaver and Millard Counties in central Utah (fig. 9). Sulphurdale is a small mining camp near the one deposit that has been exploited. Beaver (population 1,700) is 20 miles south of the deposits, and Fillmore, 40 miles to the northwest, the nearest railroad shipping point. Some of the deposits are accessible from U. S. Highway 91 by improved roads, and others are reached by primitive roads from State Highway 13. Highway 13 branches from Highway 91 near the center of the mineralized area at Cove Fort.

The deposits are in a region of moderate relief in the foothills of the northwestern part of the Tushar Mountains. The altitudes at the deposits vary from about 6,000 feet to about 6,200. Mountains southeast of the deposits rise to an altitude exceeding 12,000 feet. The climate is semiarid, with mild, pleasant summers. Winter temperatures are sometimes below zero, and occasionally snowstorms, accompanied by winds, hamper traffic on the highway. Juniper and pinon pine cover most of the foothills; grass and sagebrush grow in the valley west of the deposit. Water for milling and domestic uses is available from springs east of the Home mine.

Mining on the Cove Creek deposits began about a century ago, when sulfur was used by the pioneers to manufacture explosives and matches. The deposits were a source of sulfur produced in the United States from about 1890 to 1906, during which period the production from the area was approximately 1,000 tons of sulfur annually. During 1893 all the domestic production (1,200 short tons) was mined from these deposits.14/ Virtually all of the ore has been produced by open-pit mining from the Home mine. Sulfur was extracted from the ore by thermal processes until 1951, when a flotation mill was constructed near the Home mine. The operation was short-lived, and no production was reported from the property.

A plant to extract sulfur by a solution process started production in 1955.

The Home mine is in the southern part of the district. The Sulfur King, Victor Conqueror, Black, Beehive, East Purgatory, and West Purgatory mines are in the northern part of the district, 5 to 7 miles from the Home mine (fig. 9).

13/ Day, D. T., Geol. Survey, Mineral Resources of the United States, 1884.
14/ Parker, E. W., Geol. Survey, Mineral Resources of the United States, 1893.

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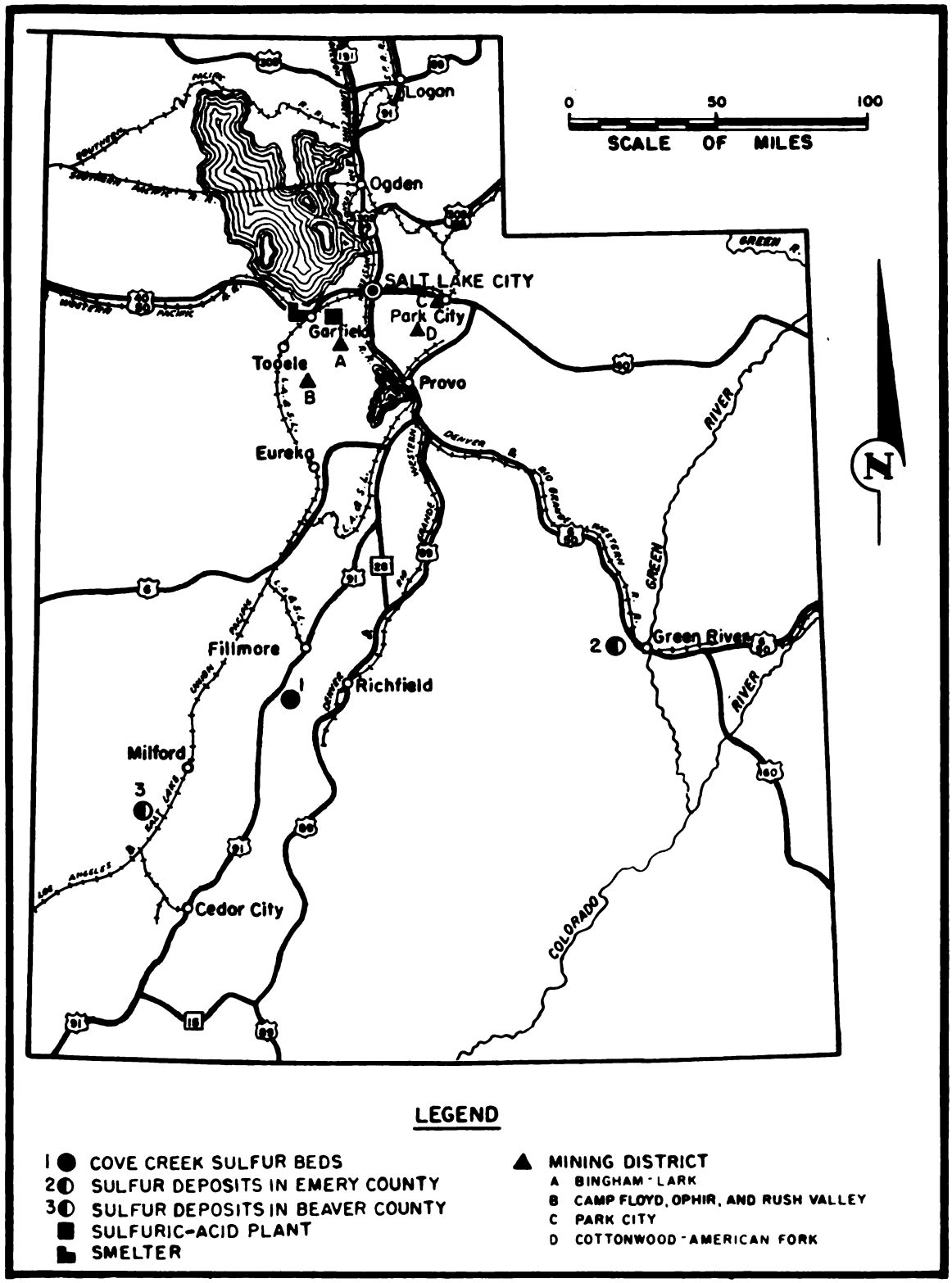

Figure 8. - Location of sulfur deposits, sulfuric-acid plant, smelter, and mining districts of Utah.

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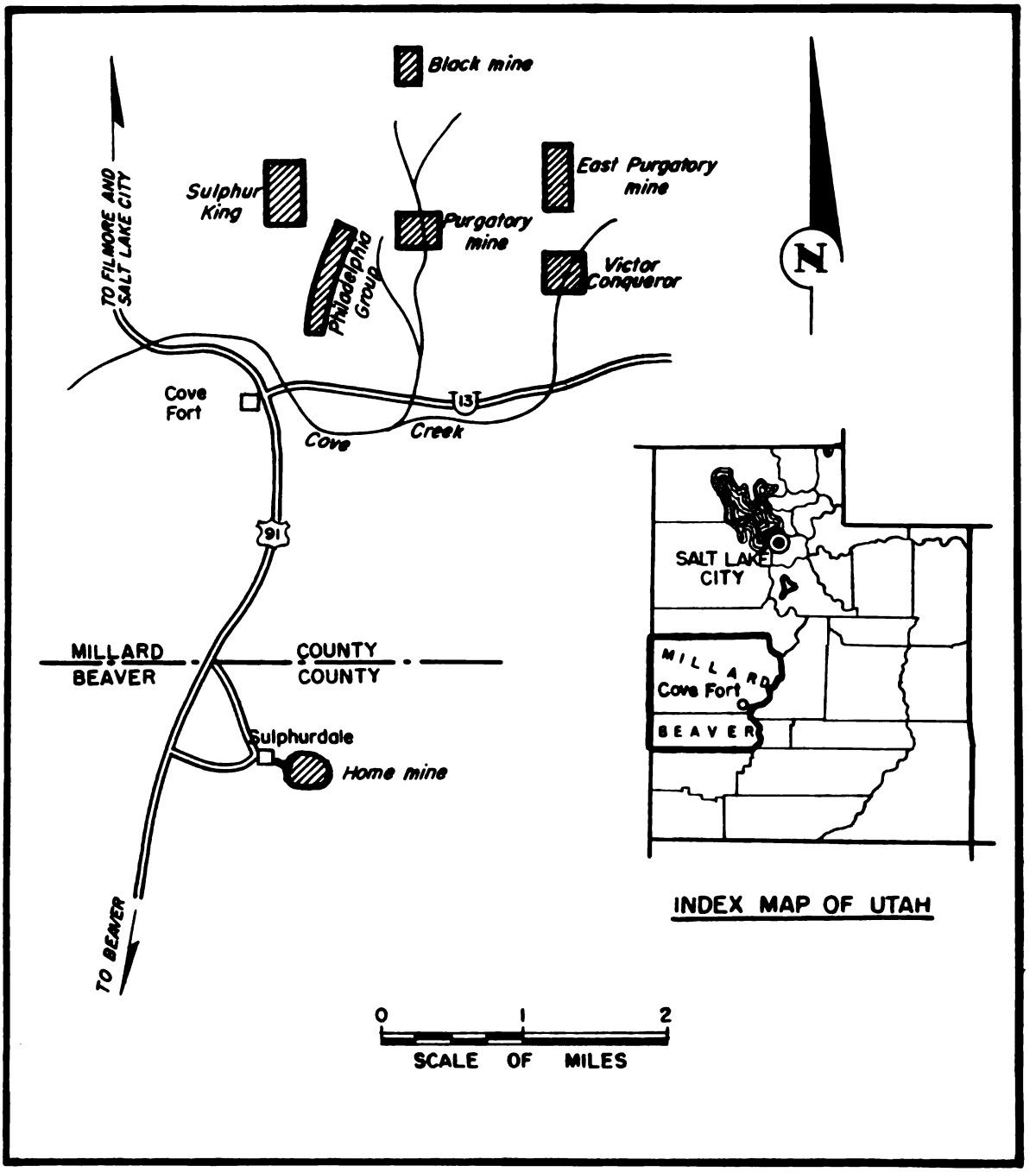

Figure 9. - Location map, principal sulfur deposits, Cove Creek sulfur beds, Beaver and Millard Counties, Utah.

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The prevailing country rocks in the vicinity of the deposits are of igneous origin. The deposits occur in soft, white, fine-grained rhyolite tuff. The tuffs and breccias, which are several thousand feet thick, are overlain in places by andesite, which in turn is overlain by basalt. The tuffs presumably rest on sedimentary rocks, the nearest exposures of which are outcrops of Paleozoic sediments in the north end of the Mineral Mountains and in the Beaver Range west of the deposits. The sediments dip easterly beneath the extrusive rocks. It is thought that the sulfur deposits are in or near a zone of major faulting.15/

The ore in the several deposits is of the same general character and probably had the same origin. The crystalline sulfur occurs in brecciated tuff, chiefly as coatings on rock fragments and as filling in cavities in the tuff. Some of the sulfur occurs in cylindrical cores 10 to 15 feet in diameter that appear to fill vents in the tuff. Sulfur also occurs in narrow, irregular veins that have banded structures. The ore extends downward into the tuff to various depths. The sulfur grades into pyrite with depth, and the thickness of the pyrite bodies is unknown. Mineralization of the tuff by sulfur is erratic, both horizontally and vertically. In places there are only small amounts of sulfur, and at others there are masses of almost pure sulfur. Springs of water rise in the bottom of the open-pit mine. The water is in constant agitation from hydrogen sulfide, and the odor of the gas is noticeable around other vents in the tuff.

Selective mining by open-pit methods has been used in exploiting the deposits because the ore is distinguishable from barren or pyrite-bearing rocks by color differentiation. Core drilling has shown that the overburden capping much of the ore is not deep, except in a few localities.

Sulfur Deposits in Emery County

Small occurrences of sulfur are found in the northern part of the San Rafael Swell in Emery County, Utah. The name San Rafael Swell was doubtlessly applied to the area in reference to the structure, which is that of a huge swell or dome in the sedimentary rocks. It is ringed by a high, nearly vertical escarpment of sandstone known as the Reef, which forms a wall or barrier that is passable in but a few places in its entire periphery. The San Rafael River is the only permanent stream in the northern part of the Swell, although some of the runoff drains into the Price River through washes north and northeast of the Reef.

There are no permanent habitations within the Swell. A few ranches along the river east of the Swell are occupied during certain seasons of the year. Green River, Utah (population 470) is the principal town in the vicinity. The main line of the Denver & Rio Grande Western Railroad and U. S. Highway 50 pass through the town.

The deposits can be reached only by horseback or on foot, as they are in areas of difficult access. The few roads that lead toward the area are little better than trails and are often impassable by automotive vehicles, especially after rains.

The southeasternmost sulfur deposit is near Black Dragon Canyon on the San Rafael River, about 14 miles westerly from Green River. It can be reached by a circuitous route from the highway 8 miles west of Green River, thence 5 miles by dirt road, and about 6 miles by horseback. The sulfur occurrence is near springs

15/ Geology in part from Lee, W. T., The Cove Creek Sulphur Beds, Utah: Geol. Survey Bull. 315 (q), 1907, pp. 485-489.

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on the south bank of the river in a narrow strip of land about 300 yards long and 25 yards wide. The odor of hydrogen sulfide can be detected about a mile away as the deposit is approached from downstream.

The springs issue through debris derived from sandstone and impure limestone. The soil adjacent to the springs, both active and inactive, is impregnated by sulfur, which occurs as cementing material between fragments of rock and particles of soil. Some of the sulfur occurs as small, yellow crystals, but a large part of it is a dirty, yellowish color and some of the higher grade material is almost black, probably stained by hydrocarbon. The river has eroded a side from one of the largest deposits of sulfur-impregnated soil. The deposit is about 50 feet long by 25 wide, and the bottom of the sulfur mineralization is exposed in the cut bank, which is not more than 10 feet in height.

The sulfur occurrences near Mexican Bend lie 6 to 8 miles northwest and up the river from those near the mouth of the Black Dragon Canyon. Black Dragon Canyon and the Barrier Reef between the deposits are impassable to travel. The deposits are reached by traveling dirt roads from Woodside, and thence by horseback over rough terrain. Woodside is a station on the Denver & Rio Grande Western Railroad, 22 miles northwest of Green River.

The sulfur occurs in small crystals and as earthy material cementing soil and rock fragments. It is pale yellow to gray. The deposits appear to have been formed around vents and do not cover any appreciable area.

Other sulfur deposits have been found on Cedar Mountain about 15 miles northwest of the Mexican Bend deposits. These deposits also can be reached from Woodside by automobile and horseback. They are associated with springs and generally similar to other deposits in the county, in that they are small, and sulfur cements soil to form a low-grade ore. The mineralized rock of the deposits is pale yellow to gray.

All sulfur deposits in the county evidently belong to the common type formed by the oxidation of hydrogen sulfide emitted from springs or from vents in the enveloping rocks.

Sulfur Occurrences Near Milford, Beaver County

A small, surficial deposit of sulfur has been found in the southwestern part of Utah, near Milford, Beaver County. The occurrence is associated with springs of cool water. The deposit lies at the southern end of Wah Wah Valley in an isolated area in which there are no permanent habitations. The Wah Wah Valley is a broad valley between two north-south-trending ranges. The deposit is about 28 miles by dirt road west and south from Milford (population 1,400), which is on the main line of the Union Pacific Railroad and is also situated on State Highway 21.

The climate of the area is arid, and there are no permanent streams near the deposit. The summers are mild and pleasant, and winter temperatures seldom fall below zero for extended periods.

The rocks exposed in the low mountains in the vicinity of the deposit are Paleozoic (?) sediments and igneous extrusives. The valley floor is mantled by alluvium. The deposit occurs on a low, isolated hill that rises about 100 feet above the valley floor. The hill is composed of limestone, and cool water springs flow from near its base. The deposit was explored many years ago by an opencut, an adit, and an inclined winze. The exploratory work reveals that the deposit has little lateral and vertical extent, as the sulfur content decreases rapidly away from a central core.

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Sulfuric Acid Production in Utah

Sulfuric acid is manufactured in conjunction with copper smelting at Garfield, Utah. Two other smelters, one at Tooele and the other at Midvale, do not produce sulfur or sulfuric acid as a byproduct.

Garfield is 20 miles west of Salt Lake City near the south shore of the Great Salt Lake and the northern end of the Oquirrh Mountains. The Union Pacific and Western Pacific Railroads both serve the area. A short electric railroad connects the smelter with the mills of the Kennecott Copper Corp., a few miles eastward. U. S. Highway 40 and 50 passes near the town.

> The American Smelting & Refining Co. experimented for many years to find a method to reduce the quantity of sulfur in the smelter fumes from the Garfield smelter, and at the same time utilize the sulfur. The local demand for sulfuric acid was not large at the time the experiments were started, and the work was directed toward production of elemental sulfur. The first method used was to pass gas, that had been concentrated and diluted to approximately 30 percent sulfur dioxide, through incandescent coke. Sulfur, liberated by the reduction of sulfur dioxide, was recovered by condensation. In 1938 experimental work indicated that high-grade sulfur could be produced by the reduction of sulfur dioxide by natural gas. Experimental and pilot plant operations were expanded until a semicommercial plant was producing about 5 tons of sulfur daily in 1940. The plant operated for 3 years on gas from the copper roasters that contained plus 7 percent sulfur dioxide. The plant then operated for 18 months on gas that contained 5.5 percent sulfur dioxide produced by copper converters. During these operations about 7,500 tons of 99.9 percent sulfur was shipped. The company planned to build a commercial plant in 1944, but the household requirements for natural gas were so large that existing pipelines could not meet this demand and any additional industrial load.16/

As a result of the sudden increase in demand for sulfuric acid in adjacent areas, the Garfield Chemical & Manufacturing Co. began to produce sulfuric acid by the contact process. The company had produced sulfuric acid nearly 40 years ago by the lead-chamber process, but did not produce industrial and chemical-grade acids in sufficient volume to attract much demand. By 1948 about 200 tons of acid was produced daily, and new facilities were completed in 1952 which made the total production capacity about 500 tons a day. The plant has been enlarged to produce 750 to 800 tons of acid daily.

Three grades of acid are produced - 95, 99, and 105 percent. The 105 percent is known as oleum or fuming acid, and is used in manufacturing explosives. Other industries in adjacent areas that use the sulfuric acid are the phosphate fertilizers, oil refineries, the steel industry, and the uranium mills of Utah and Colorado (fig. 5 and 8).

Sulfide Ores as a Source of Sulfur in Utah

The sulfide ores of copper, lead, and zinc, with the pyrite that occurs either with them or by itself, contain an important reserve of sulfur. Sulfur in ore minerals is utilized in manufacturing sulfuric acid as a byproduct of the copper-smelting

16/ Fleming, E. P., and Fitt, T. Cleon, (American Smelting & Refining Co.): Liquid Sulfur Dioxide From Waste Smelter Gases, Use of Diomethylanidine as Absorbent: Ind. Eng. Chem., vol. 42, November 1950, pp. 2253-2258.

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industry. A large tonnage of pyrite is however, rejected daily by flotation mills in Utah that could be used, if the need for the contained sulfur justified the cost of extracting the pyrite.

The copper ores produced in Utah contain over 90 percent of the total sulfur in ores normally produced in the State, and ores of lead and zinc contain most of the remainder. The reserves of sulfur from this source are contained essentially in the reserves of copper ore at Bingham Canyon. To these reserves can be added the sulfur in the lead-zinc-pyrite ores produced in the Bingham-Lark, Park City, Stockton, and other mining districts. Tailings ponds impound an additional reserve of pyrite-bearing material.

Bingham-Lark District

The Bingham-Lark district, Salt Lake County, is situated on the east slope of the Oquirrh Mountains, about equidistant from their northern and southern ends. The Oquirrh Mountains are one of the ranges of the Basin and Range Province and are narrow and short. The maximum altitude of the mountains west of Bingham Canyon is between 9,000 and 10,000 feet.

The towns of Bingham Canyon, Copperton, and Lark are connected with Salt Lake City and other towns of the Salt Lake Valley by hard-surfaced highways. A branch line of the Denver & Rio Grande Western Railroad serves Lark, and an electric railroad hauls ore from the Utah Copper mine at Bingham Canyon to the mills at Arthur and Magna.

The rocks in the district are consolidated and unconsolidated sediments and intrusive and extrusive igneous rocks. The sedimentary rocks, of upper Carboniferous age, are predominantly quartzite, with subordinate members of limestone and shaly sandstone.

Limestone horizons are of economic importance because of their relation to ore deposition. The lead-zinc and some of the copper ores produced in the district are mined from replacement deposits at favorable horizons in limestone near their intersections with fissures.

Ore deposits are associated with intrusive rocks, which occur as irregularly shaped stocks, dikes, and sills. The two largest intrusive bodies are the Utah Copper stock, which contains a large body of disseminated copper ore, and the Last Chance stock, from which lead and zinc have been produced.

The ore body of the Utah Copper Division, Kennecott Copper Corp., is of the type generally known as a "porphyry copper." Chalcopyrite, chalcocite, covellite, and bornite are the chief copper minerals in the ore. They occur, with pyrite, in a highly altered quartz monzonite. The results of petrographic-chemical analyses are:

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		Percent
Pyrite		2.15
Chalcopyrite	1.66	
Bornite	.14	
Chalcocite	.18	
Covellite	.19	
Total copper sulfides		2.17
Total sulfide minerals		4.32[17]

The recorded production of the mine from the beginning of mining in 1904 through 1954 is 706,060,974 tons of milling ore.

The ore is treated by concentrators at Arthur and Magna, about 12 miles north of Bingham Canyon. The gangue and much of the pyrite are separated from the copper minerals. The gangue and pyrite are impounded in tailings ponds, which contain immense tonnages of low-grade pyrite reserves.

The copper ores produced from replacement-type ore bodies contain more pyrite than do the lead-zinc ores from the same type of deposits. There are places, however, where both the copper and lead-zinc ores grade into pyrite. Most of the lead-zinc ore now produced from the district contains 12 to 15 percent pyrite, and the calculated sulfur content of the galena, sphalerite, and pyrite in the ore totals about 12 percent. The ore is milled at Midvale, Utah. Tailings ponds near the mouth of Bingham Canyon contain additional reserves of pyrite.

Camp Floyd, Ophir, and Rush Valley Districts

The Camp Floyd, Ophir, and Rush Valley mining districts lie within an area just south and southwest of the Bingham-Lark district. This area includes a little more than the southern half of the Oquirrh Mountains and includes parts of Salt Lake, Tooele, and Utah Counties. The Los Angeles and Salt Lake line of the Union Pacific Railroad system passes through the area west of the mountains in a north-south direction, and a hard-surfaced highway more or less parallels the railroad. Bauer, Stockton, St. John, and Ophir are small settlements within the area. Mercur, once a thriving mining community, is now deserted.

Pyrite is the most abundant and widespread sulfide in the region. It occurs associated with sulfides of base metals and as sporadic crystals in hornfels, rhyolite, and monzonite, remote from other sulfides.

The sulfide ore mined from the Ophir Hill Consolidated mine, one of the largest producers in the area, averaged about 6 percent lead, 6 to 7 ounces silver to the ton, 4 to 8 percent zinc, 12 percent iron, and 42 percent insoluble material. The calculated sulfur content for the galena, sphalerite, and pyrite in the ore would total about 18 percent. Some ore containing 4 to 5 percent copper was also shipped from the mine. This ore was more pyritic than the lead-silver-zinc ore. Pyrite was found by exploration of the Ophir formation on the south, or downthrow side of the Canyon fault. The known ore bodies at the Ophir Hill Consolidated mine are depleted, but the above data are representative of much of the lead-zinc-silver ore

17/ Head, R. E., Crawford, A. L., Thackwell, F. E., and Burgener, Glen; Detailed Microscopic Analyses of the Ore and Mill Products of the Utah Copper Co.: Bureau of Mines Rept. of Investigations 3288, 1935, p. 7.

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produced in the area. A small production of sulfide ore of similar tenor containing pyrite is being produced from the Stockton district at the present time.

Park City District

Park City is on the eastern slope of the Wasatch Mountains in north-central Utah. The town is about 25 airline miles southeast of Salt Lake City. The mining district lies in three counties, Salt Lake, Summit and Wasatch. The altitude at Park City is 7,200 feet above sea level, and mountains to the west attain elevations exceeding 10,000 feet. Summers are short and cool; autumns are short; and winters are long, with deep snows and low temperatures.

U. S. Highway 40 passes near Park City, and a branch line of the Union Pacific Railroad serves the town.

The ores in the district occur as lode and bedded deposits in sedimentary and intrusive rocks. The two types of deposits are commonly associated, but some lodes and veins occur alone. The bedded deposits in the Park City formation (Permian) are the most productive. The deposits in the Jenney quartzite member of the Weber formation (Pennsylvanian) are next in order of size and grade. Some ore of poorer grade and less extent is found in the Thaynes formation (Triassic). The more productive ore bodies of the New Park Mining Co. near Keetley in the eastern part of the district are examples of fissure-vein deposits in diorite.

The ore produced in the Park City district consists of galena, sphalerite, chalcopyrite, and tetrahedrite, with pyrite as a relatively unimportant constituent of the ore.

A few deposits are composed of about 66 to 75 percent pyrite, little or no sulfide minerals of base metals, and 25 to 34 percent gangue minerals. The deposits are comparatively small and probably do not contain more than a few thousand tons.

Cottonwood-American Fork Area

The Cottonwood-American Fork area is near the intersection of the Wasatch and Uinta Ranges. It lies south and west of the Park City district. Hard-surfaced mountain roads give access to the districts. There are no railroad facilities in the area.

All ore deposits of proved commercial importance occur in sedimentary rocks, although some small veins in the igneous rock have been explored and have produced small tonnages of ore. The ore deposits in the sedimentary rocks may be classed as contact deposits, and those associated with fissures, are the more important and numerous. In general, oxidation of ores has been extended to about the level of adjacent valleys and gulches, and sulfide ores are expected below those levels.

Pyrite is abundant in all the primary ores of the area, is common also in altered rocks, and is found in some of the igneous rocks.

The pyrite in the latter-mentioned two occurrences is not in sufficient quantities to be considered an ore of pyrite. Many of the mine workings in the area are inaccessible to examination, and data covering the occurrence of pyrite has been taken from literature. A description of one of the largest deposits in the area follows:

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The deposits of the Yankee mine (in American Fork Canyon) have been classified as of three types: Placer ore, breccia ore, and fissure ore, the latter two of which contain pyrite and have been described in part as:

Breccia Ore. - On the upper levels there is a wide zone of breccia along the Live Yankee fault, consisting of black, slatey gouge and breccia. Within the zone are found large and small fragments of ore and a large amount of pyrite.

Fissure Deposit. - Much ore was taken from the Belorophan fissure in quartzite, where the vein had a width of from 1 to 20 feet. The ore minerals, pyrite, galena, sphalerite, and tetrahedrite, were irregularly distributed through the zone.[18/]

NEW MEXICO

Small, surficial deposits of sulfur occur associated with hot springs in Sandoval County. A minor tonnage of sulfur, produced from them during 1902-4, was sold in local markets. Other small deposits have been reported in Lincoln County (fig. 10).

The oil and gas fields in the San Juan Basin in the northwestern part of the State and the Permian Basin in the southeastern part of the State contain a reserve of hydrogen sulfide, which is a direct function of the reserves of oil and gas. As of December 31, 1950, the estimated reserve of crude oil was 592 million barrels, and the estimated recoverable reserve of natural gas was 6,990,670 million cubic feet.[19/] Some sulfur is produced from these sources.

Sulfide-ore deposits in the State contain a reserve of sulfur. Most of the known reserve is centralized in Grant County in the southwestern part of the State.

Native Sulfur Deposits in Sandoval County

The Jemez River Valley in Sandoval County contains many hot springs and hot-springs deposits. Sulfur has been deposited around some of the vents and fumaroles. Water temperatures at the springs vary from 50° to more than 150° F. Large volumes of gas, probably mostly CO_2, keep the water in constant ebullition. The odor of hydrogen sulfide is noticeable at the deposits.

One deposit is 4.5 miles north of Jemez Springs and another deposit, locally called Sulfur Springs, is about 13 miles north of the town. Both are accessible from San Ysidro on State Highway 44. The nearest shipping point is Bernalillo, approximately 45 miles south from Jemez Springs. Bernalillo (population 2,000) is on the Atchison, Topeka & Santa Fe Railroad. Albuquerque, the largest city in the State, is about 60 miles from Jemez Springs.

The deposits have been known locally for many years. Ore, reported to contain 60 percent sulfur, was mined for 2 years, 1902-4. The ore was mined from underground workings, not far below the surface of the Sulfur Springs deposit. Sulfur was extracted from the ore by a thermal process. It is reported that about 100 tons of sulfur was produced and sold in local markets, principally at Albuquerque.

18/ Calkins, F. C., and Butler, B. S., Geology and Ore Deposits of the Cottonwood-American Fork Area: Geol. Survey Prof. Paper 201, 1953, 152 pp.

19/ Bureau of Mines Minerals Yearbook, 1950.

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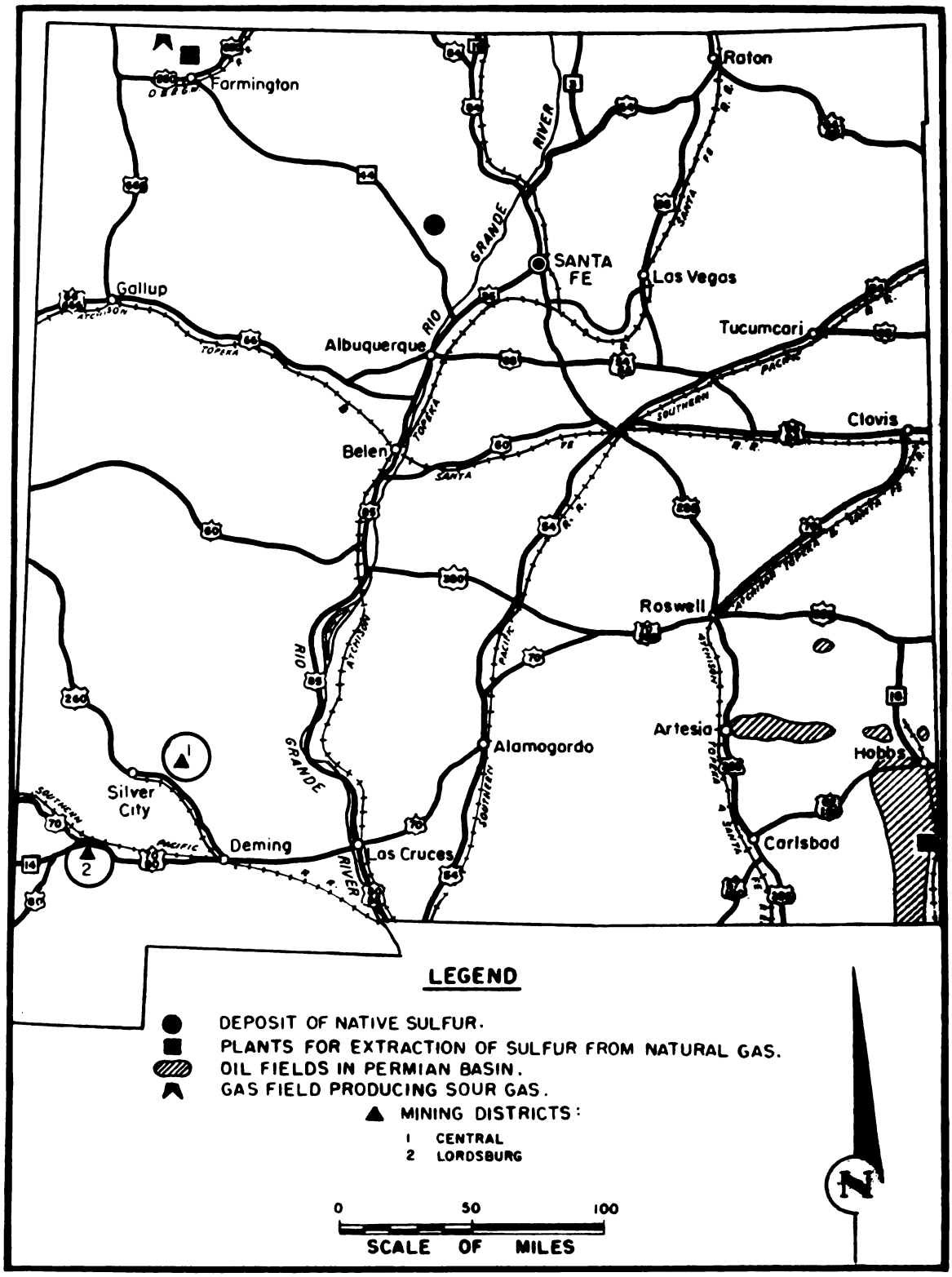

Figure 10. - Location of sulfur deposits, sulfur-extraction plants, major mining districts, and oil and gas fields of New Mexico.

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The deposit, 4.5 miles north of Jemez Springs, has formed in residual matter derived from Carboniferous limestone leached by acidulated water and permeated by sulfurous gases, which have deposited sulfur in crevices and pores of the rock. The deposit extends about 400 feet along the west bank of the Jemez River and is 60 to 75 feet wide. The western part of the deposit may have been covered by talus from adjacent canyon walls. The sulfur is irregularly deposited and is in a comparatively thin layer, measuring 2 to 3-1/2 feet in thickness. Samples of ore taken by the Geological Survey in 1918 contained between 15 and 39 percent free sulfur and 6 to 8.5 percent sulfur combined as sulfates.

The deposit at Sulfur Springs is similar, except that it occurs in rhyolite. They are numerous vents in the volcanic rock from which hot acidulated water and sulfurous vapors are being emitted. The escaping vapors have deposited sulfur in the vents, lining them with needles of sulfur crystals.

The deposit occupies a roughly circular area over 600 feet in diameter, in a small basin eroded in the rhyolite. A number of low slopes between drainage lines are covered with white debris and yellowish spots suggesting sulfur ore. From analyses, it appears that these deposits are composed of sulfates of calcium, magnesium, and sodium with minor amounts of other compounds and some free sulfur.

All the sulfur in the deposits lies within a distance of a few inches to a few feet of the surface. It also appears to be irregularly distributed in the deposits.

Sulfur Deposits in Lincoln County

Sulfur deposits near White Oaks, Lincoln County, have been described in literature, but they were not visited during the field work of 1953.[20]

Sulfur Produced From Natural Gas, San Juan County

The production of elemental sulfur from natural gas in San Juan County was begun in 1953, when a plant to extract sulfur was completed near Farmington. San Juan County is in the extreme northwest part of the State. The county occupies part of the San Juan Basin, which is structurally a broad, shallow basin that extends over much of northwestern New Mexico and a narrow area in southwestern Colorado.

Eocene beds mantle the central part of the basin, and rocks ranging in age from Cretaceous to Pennsylvanian surround the younger beds. Prominent igneous plugs and dikes are prevalent in the basin but do not occur in the heart of an anticlinal structure. Shiprock, one of the most prominent igneous plugs, rises approximately 1,850 feet above the surrounding area.

The region is arid and sparsely populated. The San Juan River flows westerly through Farmington and is the only permanent stream in this part of New Mexico. The river is maintained to a large extent by melting snow in the high mountains at its source in southern Colorado.

Natural gas was discovered in San Juan County in 1921 in a well drilled in the Southern Ute dome, near the northern boundary of the State. This well and other wells were soon after shut in until 1930, when the field was connected with a 6-inch pipeline to Durango, Colo. Production has increased since 1930 and received considerable stimulus by postwar industrial expansion. The production of the northwestern

20/ Day, W. C., Geol. Survey, Mineral Resources of the United States, 1885.

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part of the State in 1950 was 567,000 barrels of oil and 14,410 million cu. ft. of natural gas.21/ More recent data on production are not available, but the production of crude oil and natural gas has increased in the past 3 years.

Sulfurous water was encountered in the Dakota formation by wells drilled in the Chimney Rock dome and Hogback field in about 1922-26. One well flowed sulfur water for several months and then began to produce oil. Other wells that encountered water were plugged and abandoned.22/

A plant to recover sulfur from natural gas began operations in 1953. The plant is 2 miles north of Fruitland, a small town about 8 miles west of Farmington, San Juan County. Farmington (population 3,600) is the principal town in the area and the terminus of a branch line of the Denver & Rio Grande Western Railroad. It is also on U. S. Highway 550.

The natural gas processed by the plant is produced from eight wells in Pennsylvanian formations in the Barker dome. The gas, reported to contain as much as 5 percent hydrogen sulfide, is treated by a modified Claus process, using alumina as a catalyst. Some of the sulfur is recirculated and burned to form sulfur dioxide, which reacts with hydrogen sulfide to produce sulfur and water.

The sulfur is used to make sulfuric acid for the manufacture of explosives at Benson, Ariz.

Hydrogen Sulfide in Oil and Gas in Southeastern New Mexico

The oil and gas fields in the Permian Basin of southeastern New Mexico contain a reserve of hydrogen sulfide. Stripping hydrogen sulfide from natural gas was begun in 1929, and 10 plants were processing over 650 million cu. ft. of natural gas daily in 1953. Another plant began operation early in 1954. The hydrogen sulfide is removed primarily to permit utilization of natural gas as fuel rather than to conserve the hydrogen sulfide. However, two plants produce sulfur from natural gas in Lea County.

Much of the area of three counties in southeastern New Mexico - Chaves, Eddy, and Lea - lies in the Permian Basin. The basin extends far eastward and southward in Texas and is one of the major oil- and gas-producing areas in the United States. Most of the oil and gas produced in southeastern New Mexico is from fields east of the Pecos River. Elevations vary from 2,800 feet where the Pecos River enters Texas to about 3,900 feet at Lovington, Lea County, N. Mex.

The climate is semiarid, and the precipitation varies considerably from year to year. Most of the precipitation occurs from June to October, mainly as thundershowers. Although winter temperatures are generally mild, there is a large difference between the minimum winter and the maximum summer temperatures.

Most of the oil and gas is produced from reservoirs in rocks of Permian age, but some production is derived from horizons in formations that range in age from Ordovician to Cretaceous. Several grades of crude oil are produced from various fields and from different formations in the same field. The sulfur content of the oil varies from zero in many fields to a reported 4.2 percent in oil from a field just east of the New Mexico-Texas boundary. The hydrogen sulfide content of the

21/ Work cited in footnote 19.
22/ Winchester, Dean E., The Oil and Gas Resources of New Mexico: New Mexico School of Mines, Bull. 9, 1933, 223 pp.

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natural gas also varies in different fields from negligible in many fields to 0.8 percent hydrogen sulfide.

Two plants in Lea County, N. Mex., recover sulfur from natural gas produced from reservoirs in the Permian Basin. One plant is near Eunice and the other plant is at Monument. Both towns are on a branch line of the Texas & Pacific Railroad. Hard-surfaced State Highway 8 traverses the area where the plants are located.

The hydrogen sulfide content of the gas processed at other plants in the area is not high enough to justify installing sulfur-recovery facilities, and the hydrogen sulfide is burned.

Until recently hydrogen sulfide was considered a material of little value that was removed before the gas could enter transmission lines. Little effort was made to determine the hydrogen sulfide content of the gas; consequently data are incomplete and should be examined critically.

Table 3 presents data concerning the sulfur content of crude oil produced from various geologic horizons in the entire Permian Basin.23/ No data are available for the part of the basin that lies only in New Mexico.

TABLE 3. - Sulfur content of crude oils from various geologic horizons

	Geologic age	Total no. of fields of this age	No. of fields on which sulfur content data are available	Average sulfur, percent
I	Permian system			
	Tates	57	34	1.14
	Seven Rivers			
	Queen	26	7	1.04
	Grayburg	57	28	1.48
	San Andreas			
	San Angelo-Glorietta	96	28	1.48
	Clear Fork			
	Wichita	51	10	1.58
	Wolf Camp	9		No data.
II	Pennsylvanian	23	1	0.1
III	Mississippian	1		No data.
IV	Devonian	19	3	0.6
V	Silurian	11	Data uncertain	.2
VI	Ordovician			
	Simpson	17	do.	About 0.3
	Ellenburger	37	8	.2

The reserve of available hydrogen sulfide is a direct function of the reserves of crude oil and natural gas, estimates of which, for fields in southeastern New Mexico, are not available.

Sulfide Ores as a Source of Sulfur in New Mexico

New Mexico, like other States in the Rocky Mountain area, has a reserve of sulfur in the ore deposits in the State. Most of the reserve is centralized in Grant

23/ Cunningham, W. A., Hydrogen Sulfide in West Texas: Ind. Eng. Chem. vol. 42, November 1950, pp. 2238-2241.

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County in the southwestern part of the State. During 1951, 97 percent of the copper produced in New Mexico, with 92 percent of the zinc and 54 percent of the lead, was mined in Grant County. Most of this production came from what is known as the Central district, which embraces the Bayard, Fierro, Georgetown, Hanover, and Santa Rita districts. Production from this area in 1951 was 8,024,111 tons of copper ores and 634,016 tons of zinc, zinc-lead, and lead ores.24/

The Chino open-pit mine of the Kennecott Copper Corp. at Santa Rita produces most of the copper ore mined in New Mexico. The ore is milled and smelted at Hurley, 10 miles from the mine. Lead and copper concentrates and direct-smelting ores from other properties are smelted in Texas, Arizona, and Illinois, and the zinc concentrates are shipped to smelters in Arkansas, Illinois, Montana, Pennsylvania, and Texas.

Silver City, the county seat of Grant County, is roughly in the geographic center of the area that produces most of the base-metal ores mined in New Mexico (fig. 10). The population in 1950 was 7,022. Deming, approximately 54 miles southeast, is a major point of commerce in southwestern New Mexico. A branch line of the Atchison, Topeka & Santa Fe Railroad extends from Deming to parts of the Central mining District. U. S. Highway 260 passes through the area.

The geology of the Santa Rita and Hanover districts is complex. Geologic formations comprise representatives of sedimentary, metamorphic, intrusive, and extrusive rocks, ranging from pre-Cambrian to Quaternary in age. The sedimentary rocks consist chiefly of limestone and quartzite, with layers of shale interbedded in the limestone. The igneous rocks are granite, syenite, and allied porphyries, andesite breccia, intrusive rocks and lavas, stocks, and dikes. The intrusive rocks (late Cretaceous or early Tertiary) are sills or sheets of quartz diorite porphyry which have been invaded by stocks and dikes of granodiorite and granodiorite porphyry. The largest mass of granodiorite is the Hanover-Fierro stock, and the next largest is the Santa Rita stock, in which parts of the open-pit copper mine are developed.

At Santa Rita a granodiorite porphyry stock intruded Paleozoic and Mesozoic sediments and a mass of quartz diorite porphyry. The emplacement of the granodiorite was accompanied by intense fracturing, hydrothermal alteration, with sulfide mineralization and dike intrusion. Sulfides are more abundant where the fracturing has been intense and the core of the relatively unfractured granodiorite is relatively unmineralized. Much ore formed in the sedimentary formations adjacent to the granodiorite mass.

The ore bodies at Santa Rita have been enriched. Primary mineralization of pyrite and chalcopyrite accompanied alteration of fractured rock. Malachite, azurite, chrysocolla, cuprite, and native copper are found in the oxidized zone. Chalcocite and chalcocite-coated pyrite are the most abundant ore minerals in the zone of enrichment.

24/ Bureau of Mines Minerals Yearbook, 1951.

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ARIZONA

Deposits of Native Sulfur in Arizona

Occurrences of sulfur are reported in four counties in Arizona, but none is large enough to be of economic significance. The following brief description of the occurrences has been taken from a publication of the University of Arizona:25/

Cochise County. - At Tombstone, resinous, amber-yellow sulfur somewhat resembling yellow sphalerite, occurs as small crystals and replaces anglesite and galena in the Skip shaft fissure on the fourth level of the Empire mine.

Coconino County. - San Francisco Mountains in small quantities at Sunset Crater and other nearby cinder cones.

Pinal County. - Two and one-half miles east of Winkleman as tiny crystals lining small vugs in quartz vein.

Yavapai County. - United Verde mine, deposited under solfataric conditions resulting from burning of a portion of the pyritic ore body.

Smelter Gases as a Source of Sulfur in Arizona

Five smelters treated sulfide ores and concentrates of nonferrous metals in Arizona during 1953. Four of the smelters are in the southeastern part of the State and one is in the south-central part (fig. 11). Neither sulfur nor sulfuric acid is recovered as a byproduct of the smelting industry at present, although for several years sulfuric acid was manufactured from sulfur in smelter gas at Douglas.

The availability and reserves of sulfur from ore are directly dependent on the production and reserves of base metals, especially copper. 1953 may be considered as a full-production year, and data for that year may be considered indicative of the tonnage of sulfur or sulfuric acid that might be available as byproducts from the smelting industry.

From data supplied by operators of the smelters, it is estimated that approximately 500,000 tons of sulfur was contained in the smelter feed in 1953. One company estimates that the reverbatory gas at its smelter contains approximately 0.65 percent SO_2 and the converter gas possibly averages 1.1 percent SO_2.

Sulfide Ores as a Source of Sulfur in Arizona

The reserves of sulfide ores in Arizona contain a large potential source of sulfur, little of which is utilized at present. The State ranks first in the United States in production of copper, much of which is derived from low-grade sulfide ores. Most of the copper ores are associated with some pyrite, but it would be difficult to state the tonnage of pyrite rejected daily at the concentrators. Remnants of copper ore bodies in the Jerome district contain immense tonnages of pyritic material. Gold-bearing pyrite is produced as one product of milling a complex ore of gold, zinc, silver, and lead produced by a mine near Prescott.

25/ Galbraith, F. W., Minerals of Arizona: Arizona Bureau of Mines Geol. Series 15, Bull. 149, July 1941, 82 pp.

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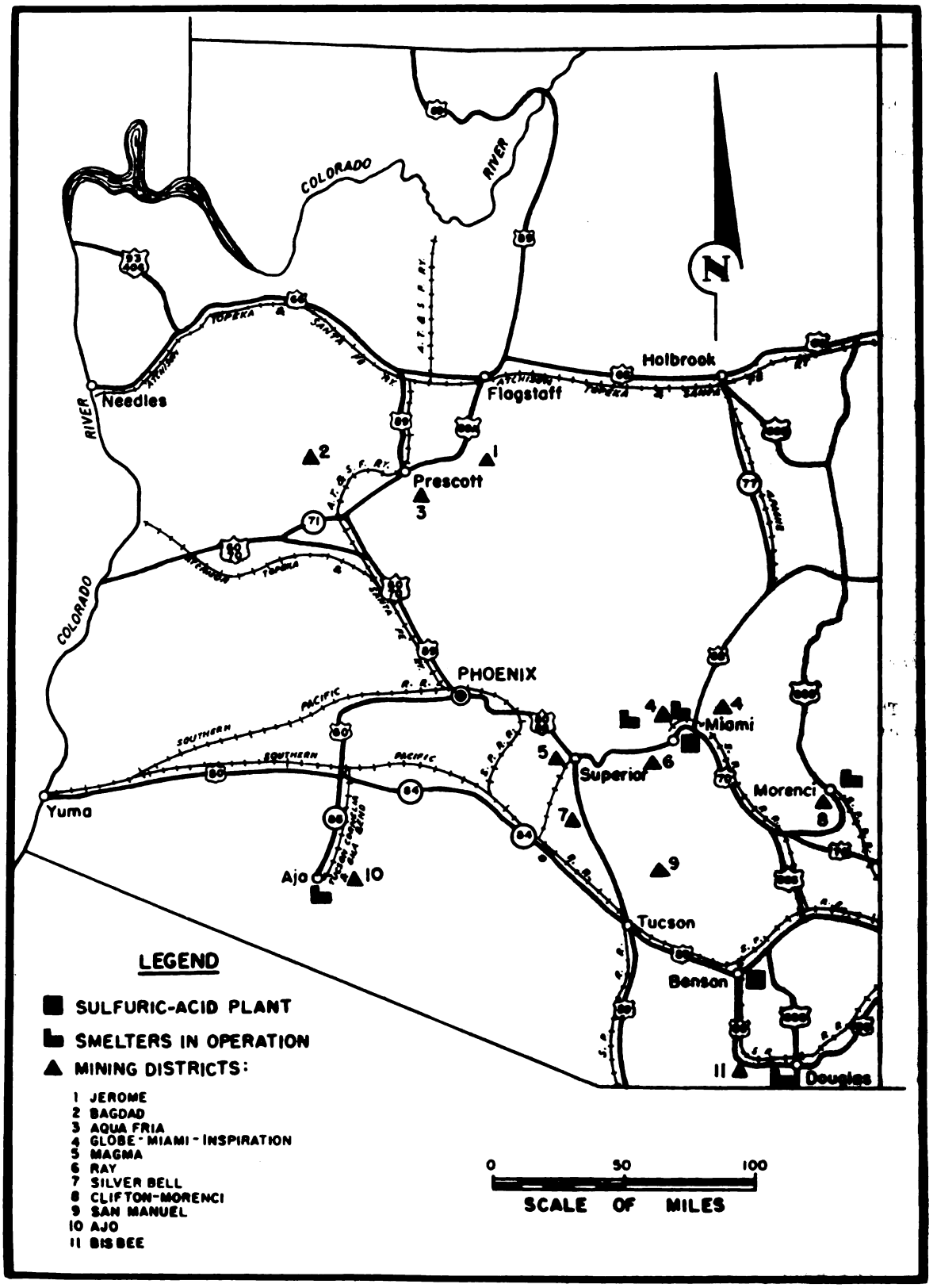

Figure 11. - Location of smelters and major mining districts of Arizona.

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In 1951 the State ranked fifth in the United States in the production of zinc and sixth in lead production. The lead concentrates were smelted at El Paso, Tex., and some of the zinc concentrates were processed at Corpus Christi and Amarillo, Tex., where sulfuric acid is made at smelters. The remainder of the zinc concentrates were shipped to Dumas, Tex., and smelters in other areas in Texas as well as in Oklahoma and Montana.

The largest mills in operation during 1951 were:[26/]

Company	Location	Product	Rated daily tonnage
Phelps Dodge Corp.	Morenci	Copper	45,000
Do.	Ajo	do.	25,000
Miami Copper Co.	Miami	do.	18,000
Do.	Castle Dome	do.	10,000
Kennecott Copper Corp.	Hayden	do.	10,000
Bagdad Copper Corp.	Bagdad	do.	4,000
Magma Copper Corp.	Superior	do.	1,500
Phelps Dodge Corp.	Clarkdale	Copper-zinc	2,100
Do.	Bisbee	Zinc-lead	900
Shattuck Denn Mining Corp.	Humbolt	Gold-zinc-silver-lead	650
Eagle Picher Co.	Tiger	Lead	500

Five copper smelters that operated in 1953 were those of the Phelps Dodge Corp. at Ajo, Douglas, and Morenci; International Smelting Co. at Inspiration; and the Magma Copper Corp. at Superior (fig. 12). From data supplied by operators of the smelters it is estimated that a total of approximately 500,000 tons of sulfur was contained in the smelter feed in 1953. Neither sulfur nor sulfuric acid is recovered as a byproduct of the smelting industry at present, although for many years sulfuric acid was manufactured from smelter gas at Douglas.

The availability and reserves of sulfur from ores depend directly on the production and reserves of base metals, especially copper. Production comparable to that of 1953 can be anticipated for many years. The decline and cessation of production from some mines are being offset by the inception of new operations, such as the recent transfer of all facilities by the Magma Copper Co. from the Castle Dome mine to Copper Cities. The new Lavender pit at Bisbee, the San Manuel ore body near Mammoth, and the Silver Bell project northwest of Tucson are recent developments in the copper industry in Arizona.

A description of the sources of sulfur in Arizona is essentially the same as that of the mining districts in the State (fig. 11). The summaries of the geology and ore deposits in the mining districts that produce more than 99 percent of the copper have been compiled principally from literature.

Jerome District

The sulfide deposits of the Jerome district constitute a large potential reserve of sulfur. The deposit of the United Verde mine is particularly noteworthy because of its size and the immense tonnage of unmined pyrite. Other deposits of pyrite in the district are known, but are comparatively small.

26/ Bureau of Mines Mineral Yearbook, 1951.

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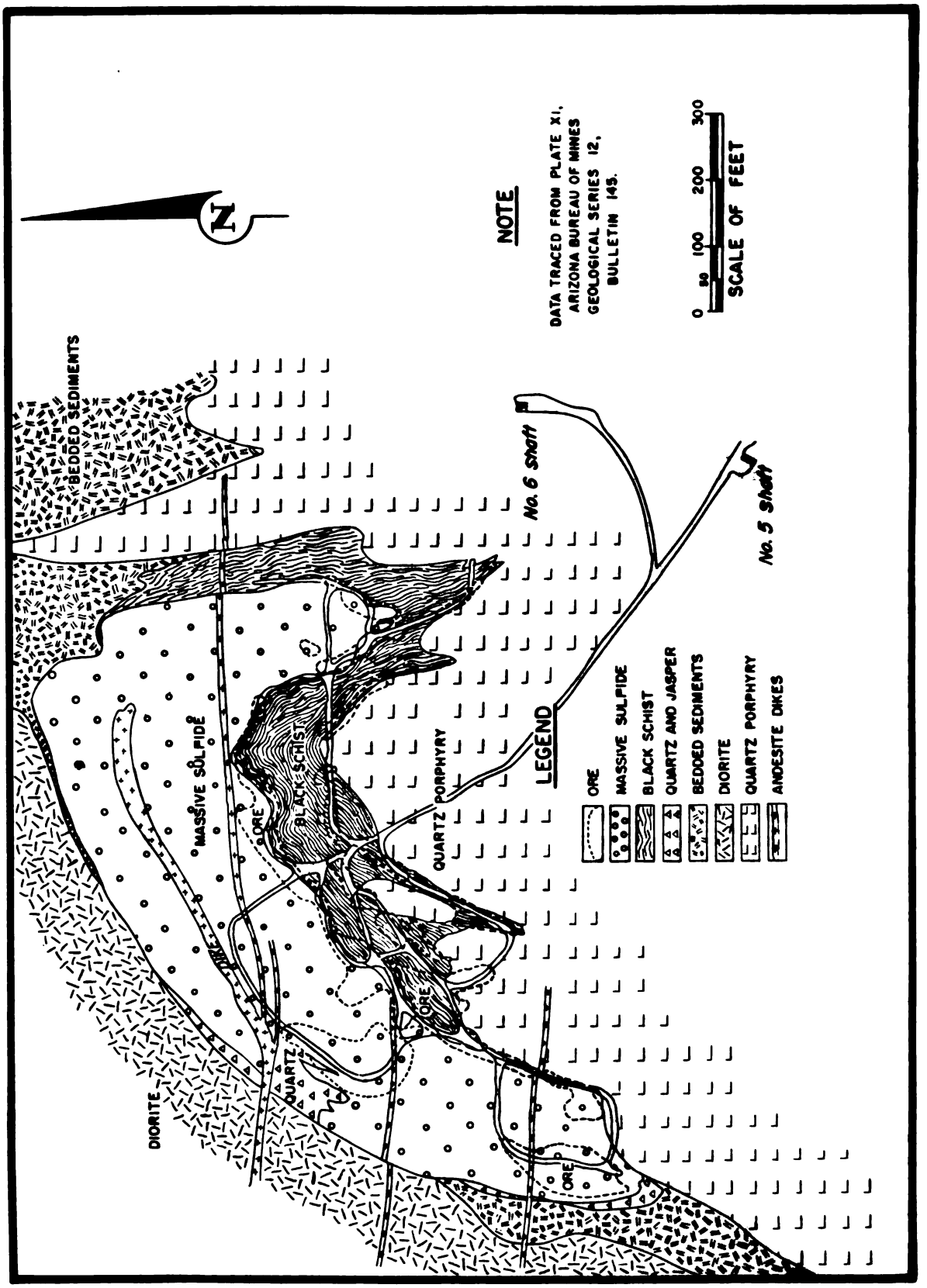

Figure 12. - Geologic map, 2,250-foot level, United Verde mine, Yavapai County, Ariz.

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Copper is the metal of greatest commercial value produced in the district, but much gold and silver and zinc also have been produced. Almost all of the ore mined in the district has been produced from the United Verde and United Verde Extension mines.

Jerome is in Yavapai County in north-central Arizona, and is situated on the eastern flank of the Black Hills at an altitude of about 5,200 feet. Clarkdale, a smelter town, is situated in the Verde Valley, 4 airline miles northeast of Jerome and 2,000 feet lower. The population of Clarkdale was 1,260 persons in 1950. The Verde Valley branch line of the Atchison, Topeka & Santa Fe Railroad passes through Clarkdale, and U. S. Highway 50 traverses the area.

> The United Verde ore zone consists of an irregular, pipelike body of massive sulfides, quartz, and mixed sulfides and rock, with a steep north-northwest plunge (figs. 12 and 13). Quartz predominates on the hanging wall or diorite side of the main sulfide mass, with the mixed material on the footwall or quartz porphyry side. In plan the main mass ranges from 500,000 square feet to less than 300,000 square feet, with an average of about 400,000 square feet. The massive sulfide itself has an average cross section of about 250,000 square feet.
>
> The downward trend of the ore zone is determined by a steeply dipping, very irregular interfingering intrusive contact between the quartz porphyry to the south and a series of banded tuffs and sedimentary material to the north. * * *
>
> * * * * * * *
>
> Although other sulfides are present, the copper content of the ore as a rule depends on the abundance of chalcopyrite. Pyrite, generally with appreciable sphalerite, constitutes the sulfide gangue. Black chlorite rock, with some quartz porphyry and quartz, is the predominant rock gangue. About one-seventh of the volume of the mineralized zone is commercial ore, and a somewhat smaller amount is possible low-grade zinc ore.27/

The analyses in table 4, although not exact averages, give the approximate chemical composition of the material of the primary mineralized zone. The sulfur content of the different types of material is of interest because of the immense reserve of the first two types listed. The table has been rearranged from the original source to present data pertinent to sulfur first in the table and to eliminate the percentages of many compounds, principally salts of calcium and magnesium.

27/ Reber, Louis E., Jr., Some Arizona Ore Deposits: Arizona Bureau of Mines, Geol. Ser. 12, Bull. 145, pp. 41-44; and Geology and Ore Deposits of Jerome District: Trans. AIME, vol. 66, 1921, pp. 3-26.

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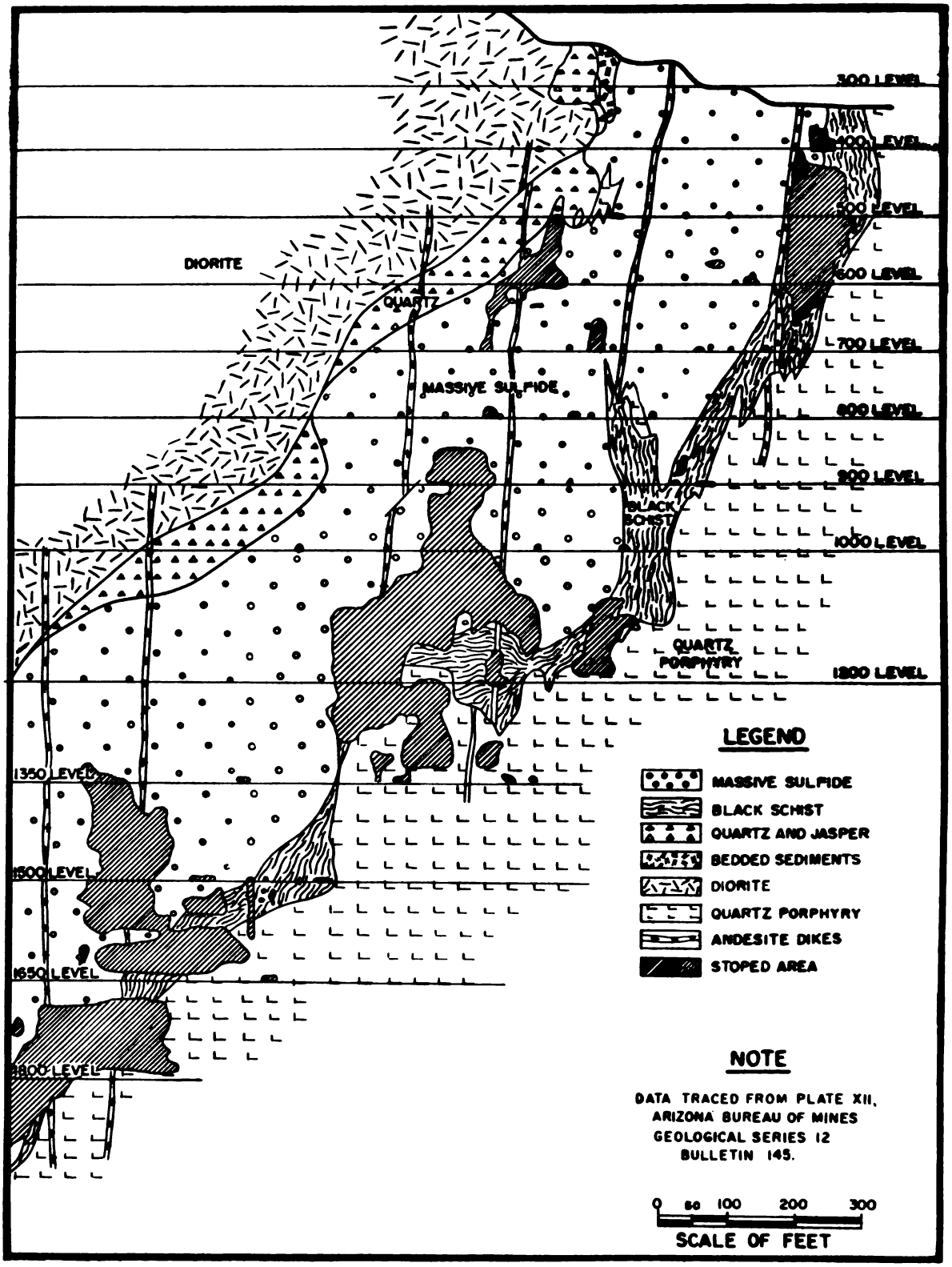

Figure 13. - Generalized geologic section, upper part of United Verde ore zone.

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TABLE 4. - Average analyses of materials in United Verde ore zone, in percent[1/]

	S	Cu	Zn	Fe	SiO_2
Lean massive sulfide	37.00	0.70	1.33	35.00	11.00
Zincky massive sulfide	38.00	1.16	6.72	33.00	11.50
Massive sulfide copper ore	32.60	4.99	2.40	31.40	11.80
Siliceous sulfide copper ore	21.30	5.44	1.90	21.40	37.20
Schist copper ore	15.40	4.73	.70	20.70	22.90
Quartz porphyry copper ore	10.80	2.79	.90	15.70	40.10
Quartz porphyry	.06	.02	.04	2.21	72.08
Black schist (chloritic)	.11	.03	.26	15.59	26.23

1/ Work cited in footnote 27.

> The ore zone of the United Verde Extension mine on the 800-foot level, near the top of the pre-Cambrian, is approximately the same size, or a little larger in area, than the top of the United Verde ore body. * * * Although primary quartz and residual pyrite are present, the primary mineralization is masked by secondary enrichment throughout the deeper parts of the mine * * *.
>
> * * * * * * *
>
> The hard, dense, lean pyrite with microscopic quartz, which is conspicuous in the United Verde ore zone, is scarce in the United Verde Extension ore zone, which contains a greater abundance of quartz-carbonate gangue.[28/]

Bagdad Mine, Eureka District

The Bagdad mine, in the western part of Yavapai County, produced much of the copper mined in that county in 1951. The mine is in the west-central part of Arizona about 67 miles by highway westerly from Prescott. Hillside, 27 miles southeast of the mine, is a station on the Atchison, Topeka & Santa Fe Railroad. The unincorporated town of Bagdad (population 850 in 1950) is on Copper Creek at an altitude of about 3,200 feet.

The ore at the Bagdad mine occurs in igneous rock, locally called monzonite, that intrudes older schists and granite. Following the later intrusive activity the rock was highly fractured, with some movement. The fractures show many directions and attitudes that are not readily reduced to definite systems.

Like most of the copper deposits of the southwest, the Bagdad deposit can be separated into three zones, namely: The oxidized zone, the zone of sulfide enrichment, and the primary lean sulfide zone. The present surface is rather free from copper stains and appears to be rather completely leached of any copper that may have been present. Generally, the amount of copper in the oxidized zone increases with depth, and in places just above the secondary zone, it may approach the copper content of the sulfide zone.

28/ Work cited in footnote 27.

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The secondary sulfide zone consists of veinlets of pyrite and chalcopyrite partially replaced by chalcocite. The copper content of the enriched sulfide zone in general is highest just below the oxide zone and gradually decreases toward the primary zone. The thickness of the enriched zone varies considerably.

Pyrite and chalcopyrite are the minerals present in the primary zone, and the copper content in general does not appear to exceed 0.5 percent.29/

Agua Fria (Big Bug) District

The mill processing ore from Iron King mine produces pyrite as a product of the beneficiation of complex sulfide ores that contain gold and silver. The mine is 12 miles east of Prescott, Yavapai County, in the low foothills of the Agua Fria mining district.

Prescott, population 6,700 in 1950, is in the central part of the State. A branch line of the Atchison, Topeka & Santa Fe Railroad and U. S. Highway 89 pass through Prescott.

Economic metals recovered are gold, zinc, silver, lead, a little copper, and fluxing pyrite.

> The ore occurs in a series of north-dipping shoots arranged in echelon pattern, the series extending over a length of 3,500 feet. Strike length of the shoots varies from 60 to 600 feet, and the widths from 3 to as much as 14 feet. The ore occurs in a sheared zone in pre-Cambrian chloritic schist. * * * The schists strike N. 23° E. and dip 75° NW. * * * The north ends of the shoots are enclosed in schist, while the south ends usually extends at full width beyond the economic limits in a pyrite-quartz, low-grade material.
>
> The plane of demarcation between the ore and the schist is very sharp, with little or no impregnation of the schists by sulfide, especially on the footwall side. The footwall schists are usually firm and strong, and have a silky texture. The hanging wall, for a width of 50 to 80 feet, consists of alternating sheetings of pyritic and chloritic schists.
>
> * * * * * * *
>
> The ore is usually hard, dense, and abrasive. The minerals are finely crystallized, with considerable intergrowth and interlocking * * *.
>
> * * * * * * *
>
> Pyrite constitutes nearly one-half of the mine ore, and carries a relatively large part of the gold in the ore. Silver has a definite relation to copper and is present to some extent at least as tennantite. The zinc varies in range from light-colored, free-floating to dark-colored marmatites. Chalcopyrite and arsenopyrite are also present in small quantities, and are host minerals for gold and silver.30/

29/ Geology from Butler, B. S., and Wilson, E. D., Some Arizona Ore Deposits: Arizona Bureau of Mines Geol. Ser. 12, Bull. 145, 1938, pp. 98-103.

30/ Mills, H. F. (Manager, Iron King Branch, Shattuck Denn Mining Corp.), Occurrence of Lead-Zinc Ore at the Iron King Mine, Prescott, Ariz.: Trans. AIME, Vol. 178, 1948, pp. 218-221.

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Globe, Miami, Inspiration Area

The copper-producing districts in the vicinity of Globe and Miami are considered as a unit because of their close proximity. The area is in southeastern Arizona about 80 miles by highway east of Phoenix.

Globe (population 6,400), Miami (population 4,300), and Claypool (population 2,000) are the principal towns in the area. A branch line of the Southern Pacific Railroad serves the area. Highways U. S. 60 from the northeast and U. S. 70 from the southeast join at Globe and continue westward through the area to Phoenix and beyond.

> Although several geologic formations occur in the Miami-Inspiration districts, comparatively few are immediately connected with the ore deposits. They may be enumerated as the Pinal schist, Pioneer shale, diabase, Willow Springs granite, Schultze granite, diorite and Gila conglomerate. * * * Most of the ore, however, occurs in the Pinal schist and the Schultze granite. The Schultze granite is roughly divided into two parts by a constriction. The northern lobe is largely porphyritic. This granitic porphyry has been minutely fissured and the cracks have been filled with quartz and, to a less extent, with sulfides. * * *
>
> * * * * * * *
>
> The metallic minerals of interest occurring in the Miami-Inspiration districts are native copper, native silver, molybdenite, galena, chalcocite, covellite, chalcopyrite, pyrite, cuprite, malachite, azurite, and chrysocolla. * * *
>
> * * * * * * *
>
> Examination of almost any specimen shows that the separate particles of copper minerals are not disseminated evenly through the mass of the rock, but to a large extent they lie in minute cracks and joints.
>
> * * * * * * *
>
> The bodies of copper ores at Miami and Inspiration may be generally characterized as undulating, flat-lying masses of irregular, horizontal outline and variable thickness. As a rule these masses lack definite outline. In general, the bottom of the leached and oxidized zone is a fairly definite, but uneven undulation surface, and as a rule the transition downward from the oxidized zone to ore is less gradual than the gradation from ore to underlying low-grade material.31/

Magma (Pioneer) District

The Pioneer district is in Pinal County, south-central Arizona. Superior (population 4,500 in 1950) is the most important town in the area. The Pioneer

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31/ Rubly, G. L., Some Arizona Ore Deposits: Arizona Bureau of Mines, Geol. Ser. 12, Bull. 145, 1938, 136 pp.

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district is 15 miles southwest of the Miami district and approximately 11 airline miles northwest of the Ray district. Phoenix is westerly from Superior approximately 65 miles by highway. U. S. Highway 60 and 70 passes through Superior, and the town has railroad facilities (fig. 11).

Superior lies at an altitude of 2,850 feet on the eastern margin of a small, basin-shaped valley between the Superstition and Pinal Ranges.

The Magma mine of the Magma Copper Co. is the largest producer in the district and one of the most important producers of gold, silver, copper, and zinc in the State.

The rocks at the Magma mine are essentially the same as those in the Ray district. The oldest formation, the Pinal schist (early pre-Cambrian) is unconformably overlain by the late pre-Cambrian Apache group. The Apache group normally consists of conglomerate, shale, quartzite, and limestone, with a total thickness of about 855 feet. It is overlain by 400 feet of Middle Cambrian quartzite, succeeded by 340 feet of Devonian limestone, 175 feet of Mississippian limestone, and 800 feet of Pennsylvanian limestone.

The Apache and older rocks are intruded by large masses of diabase. In the Magma mine it forms two sills that have invaded the shale and quartzite and engulfed limestone. Dikes and sills of quartz monzonite porphyry intruded the Naco (Pennsylvanian) limestone and underlying formations. One of these dikes is followed by the Magma vein and fault. The Magma fault is not a single dislocation but a zone of closely spaced fractures 5 to 40 feet wide, with well-defined footwall and hanging wall. It strikes about N. 80° E. Its dip above the 800-foot level averages about 70° north; but below the 900-foot level, it dips 80° south. The reversal of dip occurs where the dominant wall rock changes from sedimentary rock to diabase (fig. 14). Much later than the Magma fault and later than the dacite are the Main and Concentrator faults, between which is a mosaic of fault blocks.

Exploration of the Magma vein for a length of 8,700 feet and to a depth of 4,000 feet has revealed 3 groups of ore shoots. Most of the production has come from the main or middle ore body. The west ore body was found west of the main fault below the 2,250-foot level. This body consisted of copper ore, now mined out. The east ore bodies consisted of zinc-copper ore. Considering the size of the Magma ore bodies, the outcrop is inconspicuous. Above the main ore body the bleached, faulted porphyry dike is stained by copper and iron. There has been no replacement of limestone by ore. The main ore body is richest where its walls are of diabase. For example, on the 3,000-foot level where the walls are mainly sediments, the ores consist of low-grade pyrite, with some streaks and admixed masses of chalcopyrite, but with very little bornite. On the 3,600-foot level, where the walls are the lower diabase sill, the ore consists mainly of bornite, together with chalcopyrite, tennantite, enargite, and chalcocite. On most of the levels, the bornite is the principal hypogene mineral, although in some places chalcopyrite predominates. Pyrite is abundant with chalcopyrite, but less so where bornite is the abundant mineral. Above the 1,200-foot level, the western branch of the main ore shoot contains no copper minerals, but consists of sphalerite and galena. Below that level, it changes abruptly to bornite-rich ore.

The west ore body was about 450 feet high by 250 feet long and 15 feet wide. The ore was composed principally of bornite with chalcocite, cuprite and native copper.

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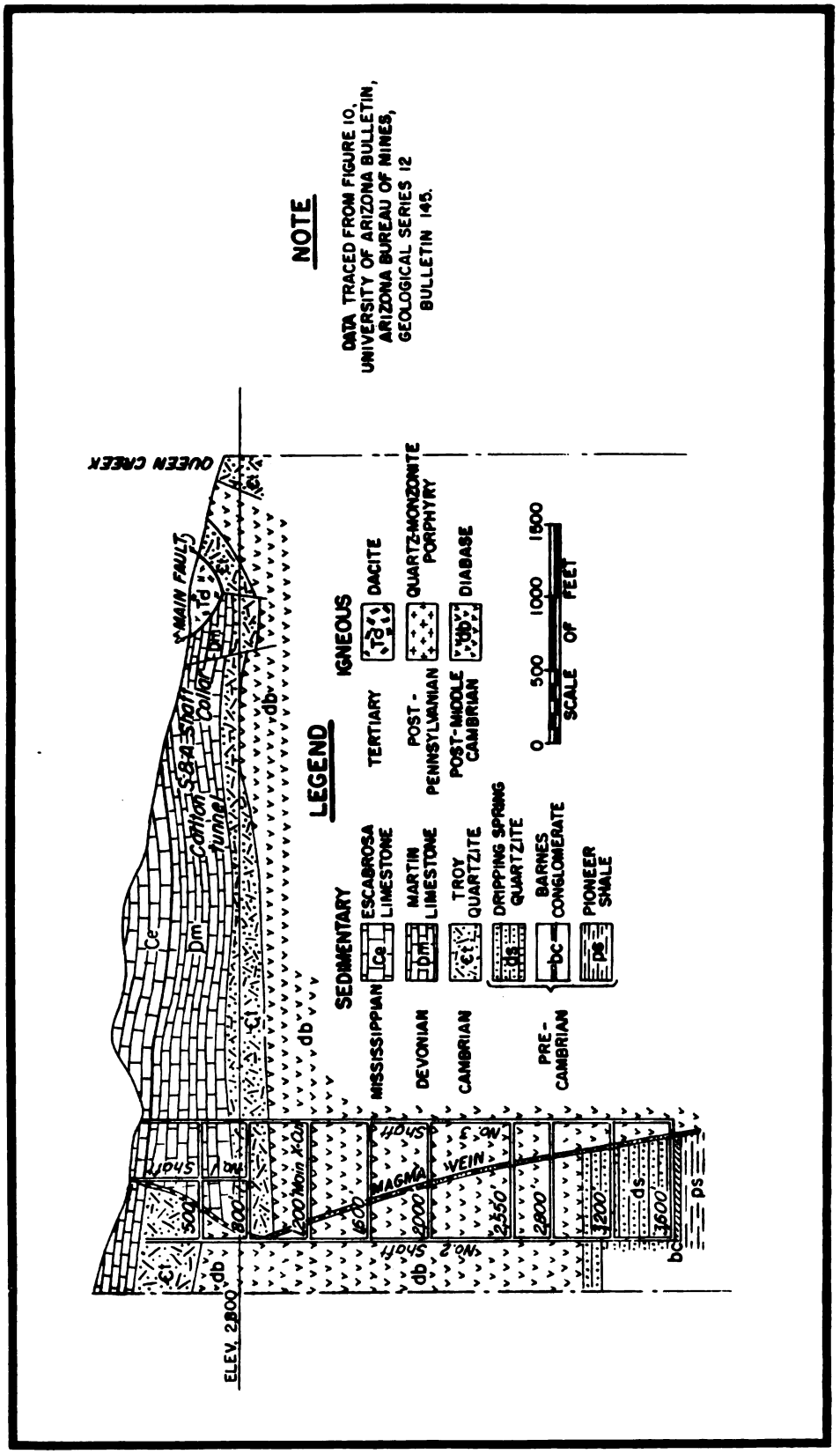

Figure 14. - North-south geologic section through shafts, Magma mine, Pinal County, Ariz.

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Several small shoots have been found east of the main crosscut. Their ore is principally sphalerite, but copper minerals are locally abundant. In places, strong oxidation extends below the 2,000-foot level.32/

Ray District

The Ray district is in south-central Arizona about 17 miles south of Miami and 11 miles southeast of Superior. The town of Ray is unincorporated and had a population of 1,000 persons in 1950. It is situated between the Dripping Springs Range on the east and the Tortilla Mountains on the west. The ores are hauled by railroad to Hayden, 26 miles southeast of Ray. State Highway 177 connects Ray with Superior on the northwest and Hayden on the southeast.

> The oldest rocks in the district are the Pinal schist, which consists mainly of metamorphosed siliceous sediments, and various granitic intrusive rocks. All these rocks are pre-Cambrian in age. Resting on the eroded surface of these crystalline rocks are the Apache group beds, aggregating 1,200 to 1,300 feet in thickness, apparently in conformable sequence and supposed to be younger pre-Cambrian. More than two-thirds of this series is represented by two quartzite formations; the remaining beds include shale, dolomitic limestone, and conglomerate. Great masses of diabase of uncertain age intrude the Apache and older rocks. Overlying the Apache group is 325 feet of limestone, thought to be Devonian. Conformably above the Devonian is the light-gray Carboniferous limestone at least 1,000 feet thick.
>
> * * * * * * *
>
> Andesitic eruptions were followed by intrusions of (1) quartz diorite, in small, irregular masses and a few fairly large dikes; (2) granite, quartz monzonite porphyry, and granodiorite in masses; and (3) quartz diorite porphyry in dikes, sills and small, rotund bodies. The time of intrusion of these three groups is not known, but it is thought to have been Laramide.
>
> * * * * * * *
>
> A period of active erosion followed the intrusions and the coarse, clastic material resulting therefrom was, in turn, buried under a flow of dacite.
>
> * * * * * * *
>
> The rocks of the district are cut by innumerable faults striking in many directions. There is scarcely any flexing or folding of the beds. * * *
>
> * * * * * * *
>
> The ore deposit is a secondary enrichment of disseminated chalcocite, associated with and partially replacing pyrite in the pre-Cambrian schist and, to a slight extent, in the Laramide porphyries. It is

32/ Geology and description of the deposits from Short, M. N., and Wilson, Eldred D., Some Arizona Ore Deposits: Arizona Bureau of Mines, Geol. Ser. 12, Bull. 145, 1938, 136 pp.

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generally referred to as a low-grade porphyry deposit. The ore body proper is a flat-lying mass, irregular in outline and of variable thickness. * * * A constriction near the center of the deposit divides it into two parts which are called the Eastern ore body and Western ore body.

* * * * * * *

Under the greater portion of the Eastern ore body, a diabase sill that slopes gently to the east and north was more highly mineralized than was the surrounding schist. Chalcopyrite associated with pyrite makes this diabase higher in copper content than the corresponding schist. * * *33/

Silver Bell Mine

The Silver Bell mine is one of the new, large-scale developments in Arizona. It is in the south-central part of the State, approximately 35 miles northwest of Tucson. The mine area is in rough, hilly country in the northern part of Pima County. Altitudes vary from 2,100 feet in the valley to 3,600 feet in the mountains. The main line of the Southern Pacific Railroad passes through Red Rock, a station approximately 20 miles northeast of the mine. The summers are hot, the winters are mild, and the annual rainfall is low.

Disseminated pyritic mineralization, with varying amounts of copper, occurs along an irregular shear zone in monzonite and other igneous rocks. The zone approaches a length of 5 miles and ranges from 1,000 to 6,000 feet in width. Numerous irregular mineralized areas of various sizes are scattered throughout the greater portion of this extensive zone. However, only two areas are known that are large enough to be of commercial importance at the present time. These two deposits, known as the Oxide and El Tiro, apparently occupy the more intensively fractured portions of the shear zone and are about 3 airline miles apart. Both owe much of their present copper content to secondary sulfide enrichment. The ore, containing chalcocite and chalcopyrite, occurs in flat, tabular masses ranging from 100 to 200 feet thick and covered by 100 or more feet of leached capping. The primary or unenriched mineralization underlying the ore contains from 0.2 to 0.4 percent copper.

Clifton-Morenci District

In 1950 and 1951 the Clifton-Morenci district was the outstanding producer of copper in Arizona and the second largest producer in the nation. The entire copper production was derived from one mine, the Morenci mine of the Phelps Dodge Corp.

The towns of Clifton and Morenci are in Greenlee County in the southeastern part of the State. Both are situated near the New Mexico line and about 130 miles north of the boundary between the United States and Mexico. Clifton (population 3,500 in 1950) is a smelter town and is situated in the narrow bottom lands of the San Francisco River. Morenci (population 6,500 in 1950) is about 4 airline miles west of Clifton. A branch line of the Southern Pacific Railroad serves the area and U. S. Highway 666 passes through the towns.

33/ Paper compiled. Arizona Bureau of Mines Some Arizona Ore Deposits: Geol. Ser. 12, Bull. 145, 1938, pp. 80-86.

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The oldest rocks of the district are pre-Cambrian granite and quartzitic schists, separated by an important unconformity from the overlying Paleozoic strata. The latter comprise a total thickness of 1,500 feet. Cambrian quartzite 200 feet thick rests on the granite and is overlain by 380 feet of Ordovician limestone, 175 feet of Devonian shale, and 170 feet of heavy-bedded Carboniferous limestone. Over limited areas, the Paleozoic strata are unconformably overlain by Cretaceous shales and sandstones. The Cretaceous, and earlier rocks, are intruded by a stocklike body, porphyritic in texture and ranging in composition from granite through monzonite to diorite. Dikes, sills, and laccoliths extend from the stock into the surrounding rocks (fig. 15).

The ore deposits may be separated into three main groups: (1) Those that replaced sedimentary rocks; (2) those that formed in fissures and as disseminations in the monzonite porphyry; and (3) fault fissure veins of the Coronado type.

The replacement deposits in limestone are principally oxidized ores resulting from the oxidation of primary ore consisting of pyrite, chalcopyrite, and sphalerite. These minerals replaced favorable strata in the limestone with material of low copper content. Oxidation changed the minerals from sulfides to carbonates and oxides with an enrichment in copper.

The deposits in the monzonite porphyry remained undiscovered for many years because the outcrops of the veins were leached and barren. After the veins were discovered, early operations were confined to the larger veins, but as it became possible to treat lower grade material, more and more wall rock was mined. Finally, it became practical to take all the material between fissures and to mine the lode zones as one ore body. At the Morenci open-pit mine, the fissures that were prominent enough to induce vein prospecting are widely spread, 300 to 400 feet apart, but between there are networks of smaller fissures that break the whole body of rock into small fragments. The mineralized body at the mine can be separated into three parts or zones: (1) The upper or leached zone; (2) the ore zone; and (3) the lean sulfide zone. The upper zone consists of iron-stained, silicified, and sericitized monzonite. The oxidized capping, from which the removal of copper has been almost complete, has a maximum thickness of 500 feet, with an average of a little more than 200 feet. The ore zone lies beneath the oxidized zone. Its blue-gray color contrasts with the buff capping rock. At close range, the network of fissures becomes prominent, and examination shows the fissure filling to be composed of quartz and pyrite, the latter being replaced to varying degrees by chalcocite. There is a rather sharp drop in copper content from about 1 percent to less than one-half percent below the zone of enrichment.

The Coronado vein occurs as a cementation of breccia on the Coronado fault, which strikes northeastward and has thrown Coronado (Cambrian) quartzite against pre-Cambrian granite. The primary mineralization is similar to that of the fissures in the monzonite porphyry, but alteration has resulted in a zone of oxidized ores and one of sulfide ores.34/

34/ Geology from Lindgren, Waldemar, The Copper Deposits of the Clifton-Morenci District, Arizona: Geol. Survey Prof. Paper 43, 1905, 375 pp.; and Butler, B. S., and Wilson, E. D., Some Arizona Ore Deposits: Arizona Bureau of Mines, Geol. Ser. 12, Bull. 145, 1938, pp. 72-77.

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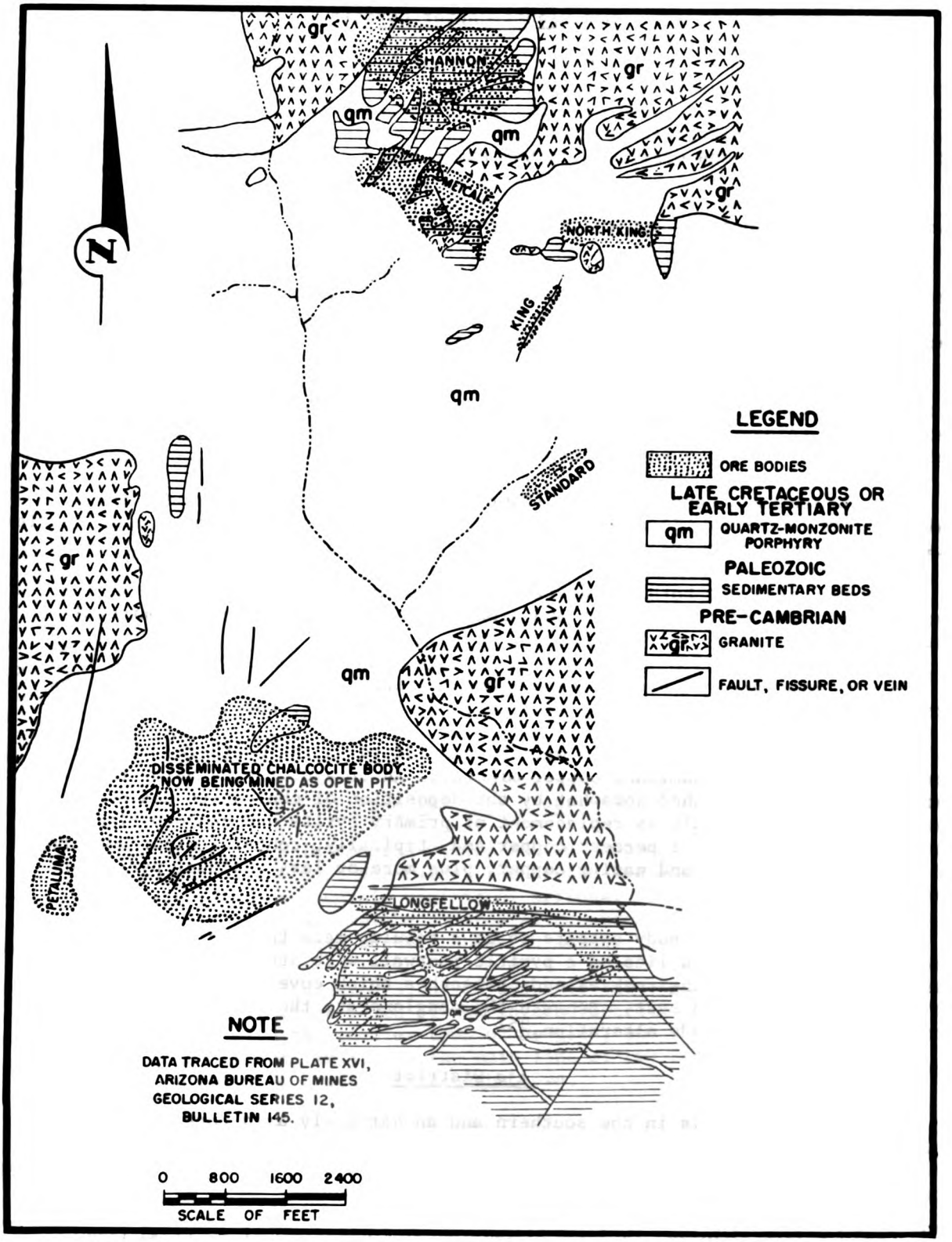

Figure 15. - Geologic map showing distribution of principal ore bodies in part of Clifton-Morenci district, Greenlee County, Ariz.

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San Manuel Copper Deposit

The mine of the San Manuel Copper Corp. has been developed recently. The property lies in the extreme southeastern part of Pinal County, 42 miles northerly from Tucson and 25 miles south of Winkleman, the nearest railroad station. The altitude at the property varies from 3,000 to 3,500 feet. The climate is typical of the southern Arizona desert, with hot summers and mild winters.

The rocks in the vicinity of the mine are the Gila conglomerate, quartz-monzonite and monzonite porphyry with intruded diabase and felsitic breccia.

The Gila conglomerate, of probable Pliocene and Pleistocene age, is a complex deposit of alluvial material interbedded with lava flows and volcanic breccias and tuffs. It covers all other rocks except those in the central and northern part of the area in the vicinity of the mine.

The quartz-monzonite is the well-known Oracle granite intrusion considered pre-Cambrian, which occupies a large area on the northern slopes of the Santa Catalina Mountains. The rock has undergone much hydrothermal action in the area and was locally impregnated with copper minerals.

The monzonite porphyry is much finer grained than the quartz-monzonite into which it was intruded. It also was affected by hydrothermal alteration and carries disseminated copper minerals in places.

Diabase dikes cut both the quartz-monzonite and monzonite porphyry in the northeastern part of the district and along the northwest of the main mineralized area.

A branching dike of barren felsite and felsite breccia cuts across all the other igneous rock. It is a very fine grained, light-gray rock.

Most of the sulfide minerals have been oxidized in the weathered zone, and chrysocolla is the predominant copper mineral. An irregular zone below the oxidized zone was enriched somewhat by the deposition of chalcocite and other secondary copper minerals as replacement of primary pyrite and chalcopyrite. The chalcocite ore averages 1 percent copper and, typically, contains minor amounts of covellite, bornite, and native copper, plus more or less residual pyrite and chalcopyrite.

The San Manuel ore body appears to be a tabular mass that coincides with the sericitic alteration and lies on a pyritic footwall with steep dip to the southeast. The copper-bearing rock extends beneath a thick cover of Gila conglomerate to the west, south, and east. Beneath the conglomerate the ore body has a steep hanging wall of low-grade alteration.35/

Ajo District

The Ajo district is in the southern and an extremely arid part of Arizona. The district lies in low desert plains at altitudes ranging from 1,700 to 2,500 feet. The topography is hilly, but not rough, with rather steep-sided hills rising abruptly above the pediments that merge into the plains.

35/ Geology from Chapman, Thomas L., San Manuel Copper Deposits, Pinal County, Arizona: Bureau of Mines Rept. of Investigations 4108, 1947, pp. 6-8.

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Ajo, Pima County, had a population of 5,800 in 1950. The town is about 42 miles south of Gila Bend on the Southern Pacific Railroad. A railroad and State Highway 85 connect the two towns.

The oldest rocks in the immediate vicinity of the Ajo ore body (fig. 16) are a series of lavas and associated tuffs, locally called rhyolites. Into this volcanic series was intruded an elongated stock of porphyritic quartz monzonite, with a discontinuous external shell of quartz diorite as much as 1,000 feet wide.

The ore body is almost wholly in monzonite, although volcanic rocks just to the southeast and southwest are also considerably mineralized. It is crudely elliptical, about 3,600 feet long and 2,500 feet wide, and has an average thickness of 425 feet. The primary ore consists chiefly of chalcopyrite, with bornite and a little pyrite distributed both in veinlets and discrete grains through the altered monzonite.

The ore body was oxidized to a surprisingly level plane near the present water level. There were local variations of as much as 50 feet; but, for the most part, the transition from sulfide to the oxidized zone was about as sharp as could be mined by steam shovel and was at nearly the same altitude beneath hill and valley.

The tenor of ore is essentially the same in oxidized and subjacent sulfide ore, with a rather insignificant quantity of chalcocite. In this respect the Ajo ore body differs from all the other great disseminated deposits of the Southwest, in each of which supergene chalcocite enrichment was essential to the production of commercial ore.

Supergene chalcocite is found in insignificant amounts over most of the area of the pit at about the original ground-water level, but at the south end of the ore body, there is a crescentric outcrop of chalcocite ore. The zone pitches 60° south, parallel to the dip of the overlying fanglomerate, and has been followed by diamond drilling to depths below sea level. This chalcocite zone is overlain by a reddish, weathered zone containing cuprite, native copper and hematite.36/

Bisbee (Warren) District

The Bisbee district is in Cochise County in the southeastern part of Arizona. The area covers part of the Mule Mountains, one of the smaller of the isolated ranges so characteristic of mountain regions of Arizona. The Mule Mountains have a northwest-southeast trend and may be considered to extend from the old mining town of Tombstone to the Mexican border, about 30 miles.

The town of Bisbee (population 3,800 in 1950) is situated in a few narrow, confluent ravines about 7 miles north of the international boundary. Bisbee is connected by railroad with the smelter town of Douglas, and with El Paso, Tex., Deming, N. Mex., and Benson, Ariz., on the main line of the Southern Pacific Railroad. U. S. Highway 80 passes through the town.

36/ Abstracted from Gilluly, James, Some Arizona Ore Deposits: Arizona Bureau of Mines, Geol. Ser. 12, Bull. 145, 1938, pp. 86-90.

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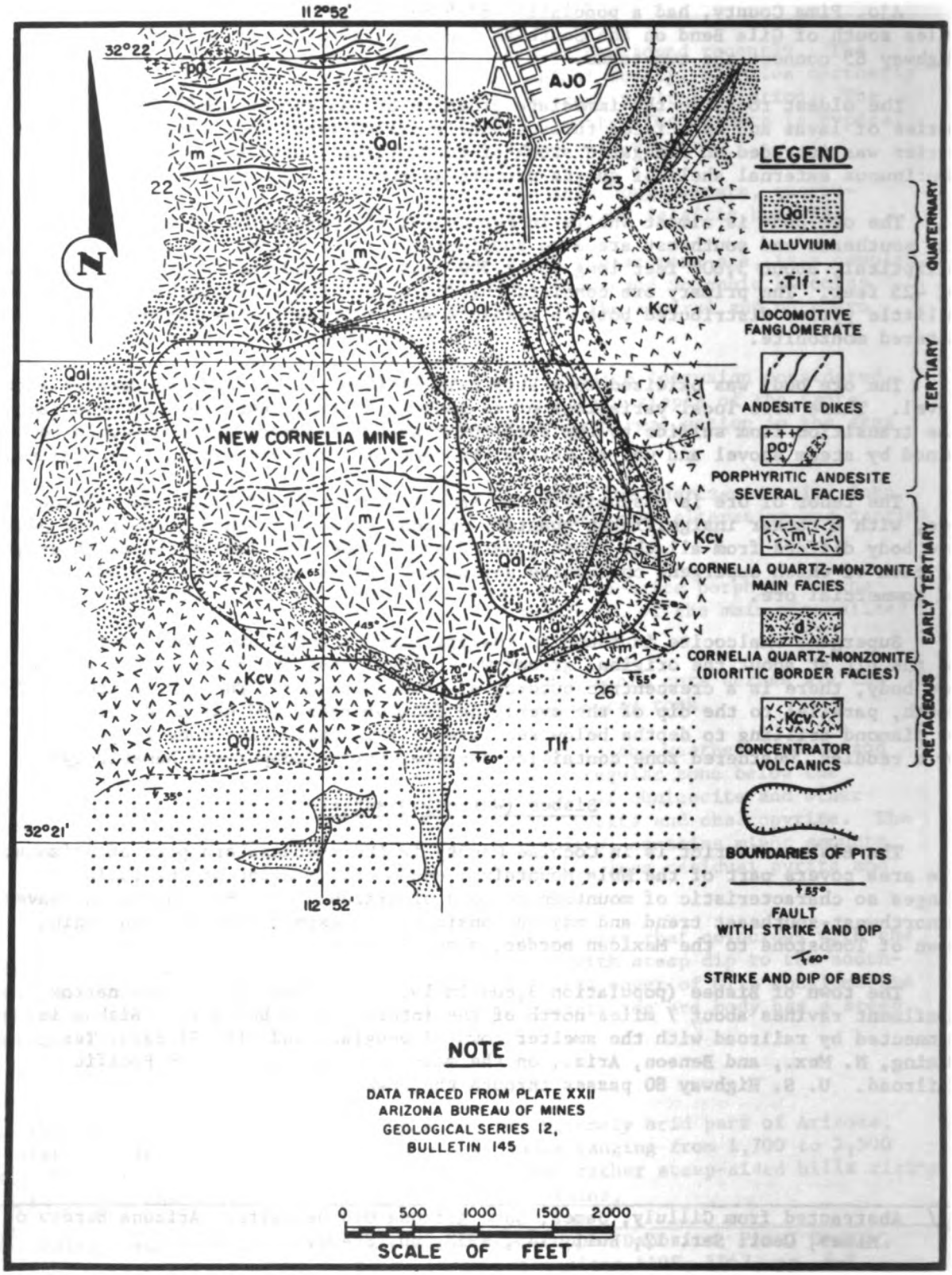

Figure 16. - Geologic map of mining area, Ajo district, Pima County, Ariz.

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The principal bodies of copper ore may be classed as replacement deposits in limestone, contact-breccia deposits, and porphyry ore bodies. The replacement and contact-breccia deposits are found in a semicircle around the granite-porphyry stock of Sacramento Hill. Some ore has been found in all the Paleozoic limestones, but in certain sections in the district, certain beds contain more ore than those above or below them.

> Practically all of the ore bodies in the district have, or had, a central core of somewhat siliceous pyrite containing small amounts of copper around which sulfides of copper and iron occurred.
>
> The pyrite core may be coarse of fine grained. In the latter case, the pyrite is commonly shattered and becomes ore because of the deposition of small veinlets of copper sulfides in breaks and cracks.

* * * * * * *

> There is a fairly large mineralized area within the stock of Sacramento Hill. * * * These ore bodies are secondarily enriched by chalcocite and are partly in the porphyry mass of Sacramento Hill and partly in the contact breccia around it.37/

Production of Sulfuric Acid in Arizona

Sulfuric acid is produced in 2 plants in Arizona, 1 at Miami and the other at Benson. The International Smelting & Refining Co. produces about 100 tons a day at Miami, where it is used in leaching oxidized copper ores. The Apache Powder Co. produces about 60 tons a day at Benson for use in the manufacture of explosives. Both plants employ the contact process and use sulfur purchased from commercial sources.

37/ Trischka, Carl, Bisbee District, Some Arizona Ore Deposits: Arizona Bureau of Mines, Geol. Ser. 12, Bull. 145, pp. 32-41.

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